Thin Metallic Heat Sink for Interfacial Thermal Management in Biointegrated Optoelectronic Devices

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The applications of modern optoelectronic devices have been extended, and they now provide practical means for seamless real-time monitoring of blood flow dynamics, by being integrated with flexible and stretchable wearable sensor platform technology. However, thermal management of these devices remains limited by undesired thermal energy originating from the heating of the light-emitting diode. Specifically, the surface temperature of the optoelectronic device becomes very high compared to that of the adjacent biological tissue, causing challenges in skin–optoelectronics integration and functional deterioration of the light source. In this study, an optoelectronic module that integrates the light-emitting diode, photodetector, and a thin metallic heat sink element for sustainable in situ thermal management is developed. Experimental and computational analysis results indicate that the proposed optoelectronic device has excellent heat dissipation capabilities for thermally safe long-term usability, due to the high thermal conductivity of the device and film-type geometrical design of the embedded heat sink for skin application. The proposed optoelectronic device architecture with metallic heat sink offers an ideal option for blood flow monitoring by providing both mechanical and thermal compatibility with biological tissue suitable for long-term clinical applications. Recent advances in wearable sensor technologies have established a foundation for active and accurate measurement of physiological signals for prophylaxis and prediagnosis.[1–6] The flexible and stretchable mechanical properties of these sensors enable conformal interfaces to curvilinear surfaces of the body and continuous collection of healthcare-related data without irritation.[7–15] Among their applications, wearable pulse oximetry has been successfully applied to monitor cardiac[16–18] and inorganic photodetector (µ-ILED) based on AlInGaP and silicon. In this configuration, specific portion of the light emitted from the µ-ILED is absorbed and scattered by biological tissues; and the rest portion of the light is transmitted through the tissues and detected its intensity by the µ-IPD. The light intensity recorded via µ-IPD of the optoelectronic device can be used to monitor internal blood flow under the skin of various parts of the body, including peripheral locations of the neck, wrist, and forehead.[21–23] Despite the well-established advantages of robust contact and functional implementation of these optoelectronic systems, undesired heating of optoelectronics and subsequent thermal damage of the skin during device operation remain as critical engineering challenges. It has been reported that the low thermal conductivity of materials in the optoelectronic interface limit effective heat dissipation, thus resulting in thermal damage to biological tissue[24,25] and deterioration in µ-ILED functionality.[26–28,38] Despite the importance of temperature control for patient safety and device operation, materials and designs to manage temperature during device operation have been less well explored.

In this study, we present materials and integration strategies of embedded metallic heat sink element in the optoelectronic device to effectively dissipate the heat generated by the µ-ILED and prevent harmful thermal damage, such as skin burn. A thin metal layer embedded under the µ-LED allows the device to maintain a low surface temperature, comparable to that of skin, via a thermally effective design based on theoretical/computational thermomechanics. Experimental results...
showed that the integrated heat sink design improved μ-ILED efficiency by maintaining a low temperature during continuous operation. Based on its advantages of being thermally safe and mechanically flexible, the proposed integrated optoelectronic device has potential utility across a range of skin- and organ-mounted healthcare systems, in which maintaining the device temperature near body temperature is a key requirement for safe operation. Figure 1a shows an exploded view of the proposed optoelectronic device to illustrate the layer information and associated components of the system. The optoelectronic device consists of a μ-ILED (peak emission wavelength: 650 nm; 400 × 200 μm²; thickness: 2 μm) obtained from an AlInGaP-based epilaxial wafer (Figures S1 and S2, Supporting Information), a μ-IPD (400 × 200 μm²; thickness: 1.25 μm) based on an ultrathin crystalline silicon membrane (Figures S3 and S4, Supporting Information), and a thin metal layer (Cu, 1400 × 1400 μm²; thickness: 16 μm; thermal conductivity, k: 400 W m⁻¹ k⁻¹) that serves as a functional heat sink element. The fabrication process begins with spin casting and thermal curing of polymethyl methacrylate (PMMA; thickness: 1 μm) as a temporary sacrificial layer and polyimide (PI) as a dielectric layer on a glass substrate. The Cu layer deposited by electrochemical deposition undergoes photolithographic patterning to create the heat sink element. A micro transfer printing technique is used to assemble the μ-ILED and μ-IPD “ink” from donor substrates to receiver substrate coated with a photocurable polymer (SU-8; thickness: 2 μm).

Figure 2 highlights the effectiveness of thermal management for the optoelectronic device associated with the metallic heat sink layer. The thermal management of solid-state lighting devices constituting the optoelectronic device is critically important as the adverse effects of excessive heating, which occur due to junction temperature rise and internal thermal resistance, lower the efficiency and deteriorate the reliability of in situ thermal management and mechanical deformability. Figure 1c shows a set of optical images of the proposed optoelectronic device during operation at ≈2 mW (left) and application on the skin (right).
of the µ-ILED. Figure 2a–d shows numerical simulation results (Figure 2a,b) and the corresponding infrared thermal images (Figure 2c,d) of the fabricated device, to compare with the surface temperature of the optoelectronic device, which depends on the presence of the heat sink element. The temperature $T$ in the device satisfies the Fourier heat transfer equation \( \nabla^2 T = 0 \) where \( \nabla^2 \) is the Laplace operator. The surface of PI has a natural convection boundary while the surface of Silbione has a constant temperature given by the thermal stage. The details of finite element analysis are given in the section of thermal analysis.

Figure 2. Interfacial thermal management for biocompatibility and device performance. a,b) Finite element modeling results and c,d) thermal images of surface temperature for the µ-ILED incorporated in the optoelectronic device. e) Surface temperature of the optoelectronic device according to the input power, with (blue dotted line) and without (green dotted line) a heat sink element. The thermal management strategy prohibits critical thermal damage to the skin: first-degree burns that result in pain and reddening of the epidermis; second-degree burns that affect the epidermis and the dermis causing pain, redness, swelling, and blistering; and third-degree burns that affect not only the epidermis and dermis, but also deeper tissues. f) Normalized light intensity with (solid blue line) and without (solid green line) a heat sink element as a function of applied current.

The temperature $T$ in the device satisfies the Fourier heat transfer equation $\nabla^2 T = 0$ where $\nabla^2$ is the Laplace operator. The surface of PI has a natural convection boundary while the surface of Silbione has a constant temperature given by the thermal stage. The details of finite element analysis are given in the section of thermal analysis. The precise thermal imager allows corresponding thermal images to be acquired for comparison with numerical predictions. Based on computational and experimental results, the surface of the optoelectronic device without heat sink element exhibits relatively higher surface temperature ($\approx 70 \, ^\circ C$) as a result of the poor thermal conductance of consisting layers in optoelectronic device, which limits the heat dissipation, leading to increased junction temperature of the device surface due to Joule heating at the active region of the µ-ILED. On the contrary, the surface temperature of the optoelectronic device with the embedded heat sink element exhibited a relatively lower temperature ($20–25 \, ^\circ C$) than the device without the heat sink element due to the immediate thermal dissipation of the device, as shown in the Figure 2b,d. Figure 2e shows the resultant surface temperature of the optoelectronic device with and without the heat sink element as a function of the applied power, as well as the potential skin burn degrees under 1 min of exposure; FEM results (dotted line) and the temperature recorded by the thermal imager (solid line) were in good agreement. The surface temperature of the optoelectronic device with an embedded heat sink increased slowly as power was applied to the optoelectronic device increases. In contrast, the temperature of the optoelectronic device without a heat sink element increased sharply as the applied power increased; in this case, the recorded surface temperature of the device exceeded the normal skin temperature, which usually ranges from 31.1 to 35.4 °C, at an applied power of ≤5 mW, which implies a high possibility of skin burn of various degrees. The results have shown that under an applied power of ≤10 mW to the µ-ILED resulting in an optoelectronic interface temperature of 50 °C, the outer layer of skin reddens (first-degree burn) after 2 min; after 10 min, lower skin layers such as the epidermis and the dermis become affected resulting in second-degree burns; and after 12 min of exposure, deeper skin tissue becomes damaged, resulting in third-degree burns. Figure 2f shows the normalized light intensity of the optoelectronic device and the effect of the heat sink element as a function of the induced current. The result indicates that the light intensity of the optoelectronic device with the
heat sink increased with the induced current; in contrast, the normalized light intensity of the optoelectronic device without the heat sink element became saturated as the induced current approached 8 mA. Functional deterioration of the µ-ILED was observed from the saturation behavior of the normalized light intensity for the optoelectronic device without the heat sink element; this behavior seemed to originate from Joule-heating effects due to the poor thermal conductivity of the optoelectronic device.\cite{38,39,43}

Figure 3a shows the schematic illustration of device configuration with the skin indicating geometrical coordinates. Based on this configuration, the systematic analysis is performed with FEM. The analysis assumes that the temperature in the device satisfies the Fourier heat transfer equation \( V^2 T = 0 \) while the temperature in the skin satisfies the Pennes bioheat transfer equation \( k_{\text{skin}} V^2 T - \sigma_b \rho_b c_b (T - T_b) + q_{\text{met}} = 0 \) with \( k_{\text{skin}} \) as the thermal conductivity of the skin, \( \sigma_b \) as the blood perfusion rate, \( \rho_b \) as the blood density, \( c_b \) as the heat capacity of blood, \( T_b \) as the blood temperature (same as the core body temperature), and \( q_{\text{met}} \) as the metabolic heat generation in the skin. The Pennes bioheat transfer equation accounts for the influences of blood flow and metabolism on the thermoregulation of skin and suffices for modeling the heat transfer in the skin. The surface of device takes the natural convection boundary. The bottom of skin has a constant core body temperature. The details of FEM for the optoelectronic device laminated on the skin can be found in the section of thermal analysis. The maximum temperature in the skin, which determines whether thermal discomfort occurs, is located at the skin surface, i.e., skin/device interface. Figure 3b shows FEM analysis results of skin surface temperature along the lateral direction (x-direction) under an applied power of 2 mW. Without the heat sink element, the temperature reaches a maximum value of \(-48^\circ \text{C}\), shows a plateau within the LED region, and then decreases dramatically outside the other regions. With the heat sink element module, the maximum temperature was lowered significantly to \(-38^\circ \text{C}\); in addition, the plateau extended from the LED region (400 µm) to the whole device region (5 mm), due to the large thermal dissipation of the heat sink element. Figure 3c shows FEM analysis results of the temperature distribution along the thickness direction (y-direction) under an applied power of 2 mW. The heat sink element lowered the temperature significantly near the skin surface. For depths \( >1.0 \text{ mm} \) from the skin surface, the influence of the heat sink element was negligible. Figure 3d shows the influence of the thickness of the heat sink element on skin surface temperature. The thermal dissipation of the heat sink element increased dramatically as thickness increased to \( 5 \mu \text{m} \); a further increase in thickness had a negligible effect.

These results are critically important to provide thermal design guidelines for optoelectronic devices laminated on skin due to device flexibility requirements.

Figure 4a–c shows photographs of the optoelectronic device laminated to skin in areas of the neck (near carotid artery),\cite{44,45} wrist (near the ulnar artery and vein, radial artery and vein),\cite{46,47} and forehead (near the cerebral artery),\cite{48} and the feasibility of extracting PPG signals to monitor respiration, cardiac activity, and brain activity, respectively. To demonstrate device viability, we applied our optoelectronics device with heat sink to the skin near the wrist and recorded the light intensity via a µ-IPD under a constant level of LED light emission. Figure 4d–f shows the data processing sequence. Figure 4d,e shows the corresponding raw data, filtered and processed with a fast Fourier transform.\cite{49} As shown in figure 4f, the peak in the frequency spectrum is \( 1.2 \text{ Hz} \), corresponding to a heart rate of 70 beats per minute (bpm). The optoelectronic device under long-term operation can monitor not only the heart rate, but also time-dynamic aspects of respiratory activity; notable differences in the light intensity level were observed during tidal breathing, as shown in figure 4g. During normal tidal breathing, the light intensity appears to have a smooth trace (i.e., minimal distortion). Upon taking a deep breath, however, the light intensity dropped sharply. Afterward, the light intensity recovered to a stable light intensity level with normal tidal breathing. The significant drop in light intensity observed when taking a deep breath was due to an increase in the blood flow, which is mainly achieved by an increase in pulse volume resulting in low light intensity.\cite{50} Figure 4h shows the light intensity variation of a constrained forearm from grasping and...
releasing the upper arm over time. While the hand grabs the upper arm once for 2 s, the plotted data indicates incremental changes in the light intensity. Repeated grabbing of the upper arm confirmed a rapid change in light intensity (e.g., high–low–high–low). Thus, the proposed device shows great potential for biomedical applications involving long-term blood dynamics monitoring, while ensuring thermally safe operation for both the device and the skin.

Recent advances in optoelectronic device technology have extended its range of use and provided practical tools for accurate monitoring of blood flow dynamics by implementing the physical and functional characteristics of wearable sensor technology. Despite these advances and benefits, challenges still remain in thermal management of optoelectronic devices due to the undesired thermal energy created during operation of the light source, such as a µ-ILED. The optoelectronic device exhibits very high surface temperatures compared with that of adjacent biological skin, which results in skin integrity issues and deterioration of µ-ILED functionality. In this study, we proposed a set of idea, design, and materials for building heterogeneous integration of optoelectronic device module that incorporates a µ-ILED, µ-IPD, and thin metallic heat sink element to provide an compelling architecture for sustainable thermal management for biomonitoring applications. Experimental and computational analysis clearly indicate that the proposed design with the integrated heat sink element dissipated heat effectively over the long term usability with thermally safe condition to the skin in the virtue of high thermal conductivity and film-type geometrical design of the embedded heat sink. The biomedical demonstration envisions that the proposed optoelectronics device having metallic heat sink enables mechanically and thermally compliant blood flow monitor to
the skin. Based on the advantages, the proposed optoelectronic device shows great potentials for biomedical monitoring, where long-term thermal control of the device near body temperature is a key requirement for safe operation (e.g., sleep studies of insomnia patients).

**Experimental Section**

**Device Fabrication:** A glass slide (50 × 35 × 1 mm²) was coated with PMMA (MicroChem, USA), which served as a sacrificial layer to facilitate release. Spin casting and thermal curing (2 h at 250 °C in a vacuum oven) of a PI film (HD Microsystems, USA; thickness: 2 µm) yielded an overcoat on the PMMA. Photolithographic patterning of Cu (16 µm) formed by electrochemical deposition with potentiostat (Interface 1010E, USA) served as a sacrificial layer to facilitate etching of the PMMA (MicroChem, USA; thickness: 2 µm) and the second SU-8 layer (i.e., the second SU-8 layer for insulation and encapsulation). 

SU-8 layers (µm) were passivated and isolated the devices. Next, multiple polymer layers (epoxy–epoxy–PMMA) were etched from regions not protected by the masking layer by reactive ion etching (100 mTorr, Dow Corning, USA) and mask aligner (MAD-400S; MIDAS SYSTEM, Korea). The material properties of the device can be found in the literature.[52] Negative photoresist (SU-8 2002; MicroChem; thickness: 2 µm) was spin coated to define the electrical contact area pattern for µ-ILED and µ-IPD electrodes. 

Bi-layers of Cr (7 nm)/Au (200 nm), formed by electron beam evaporation and patterned by photolithography, were metal-etched to create the interconnections of the device and electrical lead-out. A final layer of spin-cast negative photoresist (SU-8 2002; MicroChem; thickness: 2 µm) passivated and isolated the devices. Next, multiple polymer layers (epoxy–epoxy–PMMA) were etched from regions not protected by the masking layer by reactive ion etching (100 mTorr, Dow Corning, USA) and mask aligner (MAD-400S; MIDAS SYSTEM, Korea). Negative photoresist (SU-8 2002; MicroChem; thickness: 2 µm) was spun coated to define the electrical contact area pattern for µ-ILED and µ-IPD electrodes. Bi-layers of Cr (7 nm)/Au (200 nm), formed by electron beam evaporation and patterned by photolithography, were metal-etched to create the interconnections of the device and electrical lead-out. A final layer of spin-cast negative photoresist (SU-8 2002; MicroChem; thickness: 2 µm) passivated and isolated the devices. Next, multiple polymer layers (epoxy–epoxy–PMMA) were etched from regions not protected by the masking layer by reactive ion etching (100 mTorr, Dow Corning, USA) and mask aligner (MAD-400S; MIDAS SYSTEM, Korea). Negative photoresist (SU-8 2002; MicroChem; thickness: 2 µm) was spun coated to define the electrical contact area pattern for µ-ILED and µ-IPD electrodes. 

Device Test: Electrical measurements of the µ-ILED device were conducted using a probe station (MST 8000, MS TECH, Korea) equipped with a precision power controller (E3648A, Keysight, USA). Direct contact was made between metal pads with conductive probe tips and the p- and n-contacts of the µ-ILED. The voltage scans ranged from 0 to 1.5 V for optoelectronic device measurements.

**Thermal Image Analysis:** Thermal analysis of the µ-ILED device was conducted using a power controller (E3648A, Keysight) over a power range of 0−25 mW via interconnection to the optoelectronic device. Thermal images of the optoelectronic device were collected with a precision infrared camera (FLIR Systems, USA). The surface temperature value was analyzed by taking digital information from the camera.

**Finite Element Model:** 1) Thermal analysis of the optoelectronic device: a 3D FEM model was created in COMSOL to investigate the surface temperature of the optoelectronic device. The model, from the bottom to the top layer, consisted of a PI layer (thickness: 2 µm; thermal conductivity: 0.52 W m⁻¹ k⁻¹), the Cu heat sink element of the optoelectronic interface (thickness: 16 µm; thermal conductivity: 400 W m⁻¹ k⁻¹), the first SU-8 layer for adhesion (thickness: 2 µm; thermal conductivity: 0.2 W m⁻¹ k⁻¹), the µ-ILED (thickness: 2 µm; thermal conductivity: 148 W m⁻¹ k⁻¹) located in the center of the SU-8, the second SU-8 layer for insulation and encapsulation (thickness: 4 µm), and the last layer of Silbione (thickness: 300 µm; thermal conductivity: 0.52 W m⁻¹ k⁻¹). The thickness of the Au layer (200 nm) was much smaller than that of the other layers, such that it was reasonable to model the SU-8/Au/SU-8 (Figure 1a), as a single SU-8 layer (i.e., the second SU-8 layer for insulation and encapsulation). The lateral dimensions of the µ-ILED and other layers were 400 × 200 µm² and 5 × 5 mm², respectively, the same as those used in experiments. Power was applied via a volume heat source to the µ-ILED. 

The PI surface provided a natural convection boundary (convective heat coefficient: 7 W m⁻² k⁻¹). The surface of Silbione maintained a constant temperature of 30 °C. The material properties of the device can be found in the literature.[53]

2) Thermal analysis of the optoelectronic device laminated on skin: a 3D FEM model was established in COMSOL to study the thermal properties of the optoelectronic device while laminated on skin. The geometric dimensions and material properties of the optoelectronic device were the same as those described in the previous thermal analysis section (optoelectronic device), with the exception that the thickness of Silbione was set to 5 µm instead of 300 µm to increase the device flexibility. The skin parameters were as follows: skin thickness of 6 mm, skin thermal conductivity of 0.187 W m⁻¹ k⁻¹, blood specific heat of 3770 J kg⁻¹ k⁻¹, blood density of 1060 kg m⁻³, and blood perfusion rate of 0−0.1 mL blood/mL tissue/s. The metabolic heat generation was 368.1 W m⁻³. The core body temperature and blood temperature were 37 °C. The device surface was assumed to be a natural convection boundary with a convective heat coefficient of 7 W m⁻² k⁻¹. The bottom of the skin retained the core body temperature, which remained constant. The material properties of skin can be found in the literature.[32]

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

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III-V optoelectronics, flexible electronics, heat dissipation, pulse oximetry, thermal damage

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