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Low-Outgassing Liquid Metal–Silicone Composites for Multifunctional Space Applications

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ABSTRACT

Space-grade elastomers provide critical sealing, adhesion, and damping functions in spacecraft but require low outgassing to avoid contamination of sensitive optical and electronic components. Silicone elastomers are widely adopted due to their environmental stability, mechanical reliability, and ease of processing. Here, we introduce a multifunctional, low-outgassing liquid metal elastomer composite with a space-grade silicone matrix (S-LMEC) that combines the mechanical reliability of the silicone with enhanced thermal and electrical properties. Dispersed LM microdroplets enable a 2.3× higher breaking strain, an 11× increase in thermal conductivity, and a 9.6× increase in dielectric permittivity without hindering curing. Thermogravimetric analysis demonstrates that the embedded LM does not compromise the underlying thermal stability of the polymer matrix while active electronic testing indicates the S-LMEC significantly lowers the steady-state temperatures by promoting rapid heat dissipation. Furthermore, the material can be patterned into complex structures via direct ink write 3D printing. The outgassing evaluation of the S-LMEC indicates a total mass loss (TML) of $\leq 1.00\%$. To demonstrate practical utility, the S-LMEC was integrated into a wearable capacitive tactile glove for soft robotic skin applications. This materials platform expands the design space for space-grade elastomers, enabling advancements in planetary exploration soft robotics and on-demand electronics manufacturing.

1 | Introduction

Space-grade silicone elastomers have been widely used in the construction of spacecraft and satellites due to their unique combination of physical, chemical, and mechanical properties. They exhibit excellent thermal stability over a wide range of temperatures [1–3], optical transparency [4], resistance to ultraviolet radiation [5], and inherent electrical insulation [6, 7]. In addition, their flexibility, low elastic modulus, and high deformability provide mechanical compliance and can be easily processed [8–11]. This combination of environmental resilience, mechanical com-

pliance, and processability make silicone elastomers essential materials for aerospace applications, where they have been used as gaskets [12], sealants [13], and adhesives [14] to damp vibrations and prevent air leakage or cabin depressurization in critical spacecraft systems. Unlike conventional commercial elastomers (such as standard polydimethylsiloxane, PDMS), which contain high amounts of low-molecular-weight volatile siloxanes that outgas and condense onto sensitive optical or electronic payloads in deep space, space-grade matrices are strictly refined to meet rigorous aerospace vacuum stability standards. However, current space-grade silicones may face limitations in emerging and

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modular space systems, which require multifunctional behavior within a single material system [15].

Commercially available space-grade silicone elastomers such as NuSil CV-2644 and CV10-2568 have inorganic fillers in their formulation to improve the physical properties while maintaining low outgassing properties required for spaceflight qualification [16, 17]. Recent research has focused on the incorporation of functional fillers, majority of which are carbon-based, to further enhance functional properties in space-grade silicones. Carbon nanotubes (CNTs) and graphene are frequently employed to provide critical protection against atomic oxygen erosion and to establish electrically conductive pathways for Electromagnetic Interference (EMI) shielding and sensing applications [18]. Carbon fibers have been integrated into silicone rubber to create thermal interface materials (TIMs) for enhanced heat transfer while retaining acceptable outgassing performance [19]. Apart from these few studies on silicone composites with carbon fillers, there are limited efforts on improving the functional properties of space-grade silicones. Furthermore, these carbon fillers are typically rigid, which, when incorporated at high volume loadings, will result in the breakdown of the soft and deformable nature of the silicone. Hence, investigations into new and emerging functional fillers and careful characterization and optimization of their behavior in space-grade silicones is needed to enable multifunctional capabilities without compromising their mechanical compliance.

In non-space-grade silicone elastomers, one of the emerging ways to overcome the limitations in filler volume loadings and rigidity is to impart a liquid filler such as gallium-based liquid metal (LM), which preserves the soft and deformable nature of the matrix while enhancing various functional properties due to its metallic thermal and electrical conductivity. These LM-elastomer composites demonstrate unprecedented combinations of properties, such as high thermal conductivity [20–22], enhanced dielectric properties [23–25], self-healing [26–28], extreme toughening [29], shape-morphing [30, 31], tunable acoustic properties [32], and the ability to form electrically conductive networks under controlled mechanical pressure [33, 34]. These responsive materials can also be integrated into soft robotic systems to detect damage and autonomously self-heal to maintain functionality [26, 27], and as thermoelectric generators to convert heat produced by the human body into electric voltage for powering soft wearable devices [35]. Furthermore, these composite materials can be 3D printed using direct ink write (DIW) material extrusion techniques for on-demand, customized fabrication of complex geometries and support design for manufacturing (DFM) principles [21, 36, 37]. These and other investigations into LM fillers in silicone elastomers collectively demonstrate that LM can synergistically balance the mechanical response, thermal, and electrical functionalities. However, the addition of LM to low-outgassing space-grade elastomers to create multifunctional soft composites has not yet been explored, and could significantly expand the applications of silicones in aerospace environments beyond adhesives and sealants.

In this work, we present a systematic study of eutectic gallium-indium (EGaIn) inclusions dispersed in a low-outgassing, space-grade silicone elastomer (Momentive RTV567) to create soft, multifunctional LM elastomer composites (S-LMEC, where S denotes

the space-grade silicone matrix) toward space applications. (Figure 1A). While typical elastomeric composites compromise vacuum volatile stability, our formulation demonstrates that the low-outgassing characteristics can be preserved even at high filler volume loadings. The S-LMEC is synthesized by shear mixing LM and silicone in a planetary mixer, which generates spherical LM microdroplets with diameters on the order of 25–30 μm (Figure 1B and Figures S1–S3). The uncured S-LMEC shows processability and geometric versatility; it can either be mold-casted or DIW 3D printed to create thin films (Figure 1C). The S-LMEC is highly deformable due to its elastomeric nature and liquid-phase inclusions, thus enabling it to be stretched, folded, bent, or twisted without permanently altering the geometry (Figure 1D). The addition of LM also improves the physical properties of the silicone by enhancing its thermal conductivity, allowing it to stay cooler than the unfilled elastomer when exposed to heat (Figure 1E and Video S1). Furthermore, we systematically investigated the effects of the LM volume loading ($\phi = 0\text{--}60\%$) on the mechanical, thermal, and dielectric properties. Thermal and environmental stability measurements confirm that the embedded LM does not compromise the intrinsic thermal tolerance of the silicone matrix, while outgassing evaluations show a total mass loss (TML) threshold of $\leq 1.00\%$. Finally, we demonstrate S-LMEC's system-level performance by integrating it as a TIM for rapid heat dissipation and into a wearable, multifunctional tactile glove. The S-LMECs demonstrated here could potentially enable a versatile material platform to expand the accessible soft electronics and robotic systems for next-generation space missions.

2 | Results and Discussion

2.1 | Mechanical Properties of S-LMEC

The mechanical properties of the S-LMEC with varying LM volume loading ranging from $\phi = 0\text{--}60\%$ were investigated. Representative stress-strain curves for samples at each ϕ are plotted in Figure 2A, and the strain at break and elastic modulus values were obtained from these curves. The strain at break increases from 72.9% in unfilled silicone to a maximum of 171.6% at $\phi = 40\%$, beyond which it decreases (Figure 2B). This non-monotonic behavior is consistent with increased stress concentrations at high values of ϕ , which may reduce the effective continuity of the matrix and thus lower the fracture energy of the composite [29, 38]. During deformation, interfacial debonding between the LM droplets and the elastomer matrix is hypothesized to create localized stress concentrations and potential cavitation voids, which could serve as failure initiation sites that limit ultimate elongation [39]. Furthermore, classical linear elastic fracture mechanics (LEFM) theory suggests, and our experimental trends support, that larger inclusions and aggregated LM domains may facilitate crack propagation at lower applied stresses [23, 40]. Such microstructural features are expected to reduce the strain limit at which fracture initiates, providing a plausible explanation for the reduced stretchability observed at elevated loadings ($\phi = 40\%$) [41]. However, direct real-time visualization of these microstructural failure modes remains a subject for future in situ mechanical characterization.

Mechanical testing data reveal that the Young's modulus of the S-LMEC decreases with increasing ϕ (Figure 2C). Eshelby's

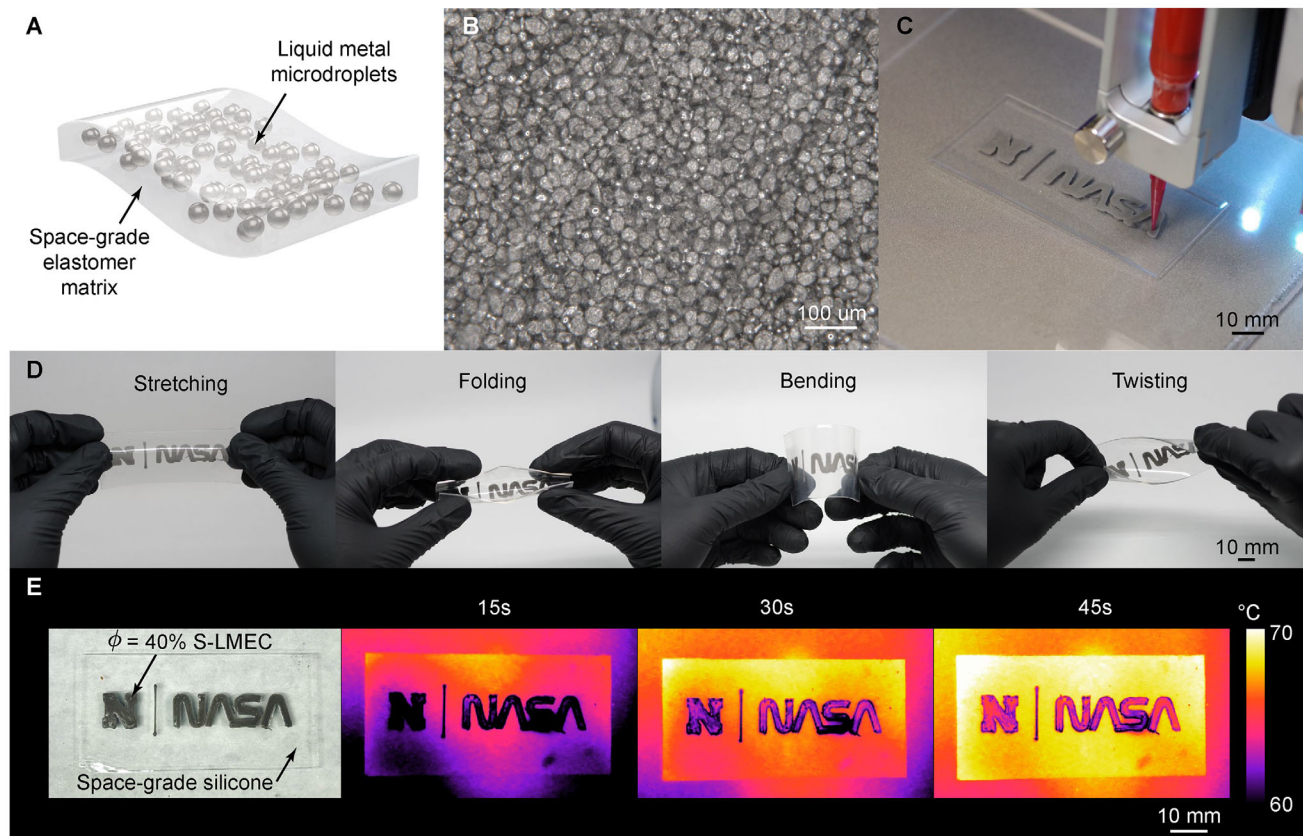


FIGURE 1 | Overview of properties of LM elastomer composites with a space-grade silicone matrix (S-LMEC) toward space applications. (A) Illustration of composite material with EGaIn microdroplets suspended in a space-grade RTV567 silicone matrix. (B) Optical micrograph of $\phi = 40\%$ S-LMEC. (C) Direct Ink Write 3D printing of the uncured S-LMEC to fabricate thin films. (D) Images showing the flexible and stretchable nature of the thin film through stretching, folding, bending, and twisting. (E) Infrared images of the printed thin film demonstrating the heat dissipation behavior.

theory of inclusions was utilized to determine the expected elastic modulus of the composite. Assuming incompressible elastic inclusions of modulus E_i dispersed in a matrix of modulus E_m , the resulting composite modulus E_c is [42]

$$E_c = E_m \frac{1 + \frac{2}{3} \frac{E_i}{E_m}}{\left(\frac{2}{3} - \frac{5}{3}\phi\right) \frac{E_i}{E_m} + \left(1 + \frac{5}{3}\phi\right)} \quad (1)$$

By utilizing values for E_m found through mechanical testing and $E_i = 320$ kPa from Bartlett et al. [43], it is observed that the elastic behavior of the S-LMEC agrees with Eshelby's theory. Three regions of inclusion stiffness are plotted in Figure 2C as a function of ϕ . These include stiff inclusions ($1 \text{ MPa} < E_i < 1 \text{ TPa}$), soft inclusions ($129 \text{ kPa} < E_i < 1 \text{ MPa}$), and fluid inclusions ($0 \text{ kPa} < E_i < 129 \text{ kPa}$). The $E_i = 129 \text{ kPa}$ threshold is derived from previous work done by Style et al. [44], in which it was shown that liquid inclusions can stiffen solids and demonstrate an effective modulus $E_i = E\{24\alpha/(10 + 9\alpha)\}$, where E is the matrix modulus, $\alpha = \gamma/ER$, γ is the surface tension of the liquid inclusion, and R is the inclusion radius. Utilizing values of $\gamma = 620 \text{ mJ m}^{-2}$, $E = 85 \text{ kPa}$, and $R = 15.0 \text{ } \mu\text{m}$ yields $E_i = 129 \text{ kPa}$. Based on these results, it is observed that the LM microdroplets behave like soft inclusions to reduce the elastic modulus of the matrix.

Figure 2D illustrates the stress-strain behavior over 100 continuous loading-unloading cycles up to 50% strain. The first cycle shows a distinct path with a prominent hysteresis loop, indicating energy dissipation common in viscoelastic materials or systems undergoing Mullins-like network rearrangement. Upon subsequent cycling, the loading path rapidly stabilizes, with cycle 10 directly overlapping cycle 1 during extension. However, by cycle 10 and continuing through cycle 100, the composite exhibits a subtle increase in peak stress (from $\sim 0.155 \text{ MPa}$ at Cycle 10 to $\sim 0.160 \text{ MPa}$ at Cycle 100, representing a minor $\sim 3.2\%$ shift). Rather than stress-softening, this slight evolution reflects mild, strain-induced polymer chain reorientation around the LM inclusions over extended testing ($\sim 160 \text{ min}$). Overall, the curves maintain a tight loop, demonstrating good mechanical reversibility and minimal fatigue after the initial mechanical conditioning. To quantify this behavior, energy dissipation was calculated from the area enclosed by the hysteresis loops. The dissipation decreases from 1.62 MJ m^{-3} in the first cycle to 0.087 MJ m^{-3} by cycle 100, confirming that the S-LMEC mechanically stabilizes over time. This stability is further corroborated by time-dependent force responses in Figure 2E. The peak force exhibited high mechanical endurance and minimal force drift, transitioning slightly from $1.85 \pm 0.01 \text{ N}$ across the first 10 cycles to $1.94 \pm 0.01 \text{ N}$ across the final 10 cycles (over a period of $\sim 160 \text{ min}$), representing a minor $\sim 4.8\%$ shift and indicating high force retention ($>95\%$) without

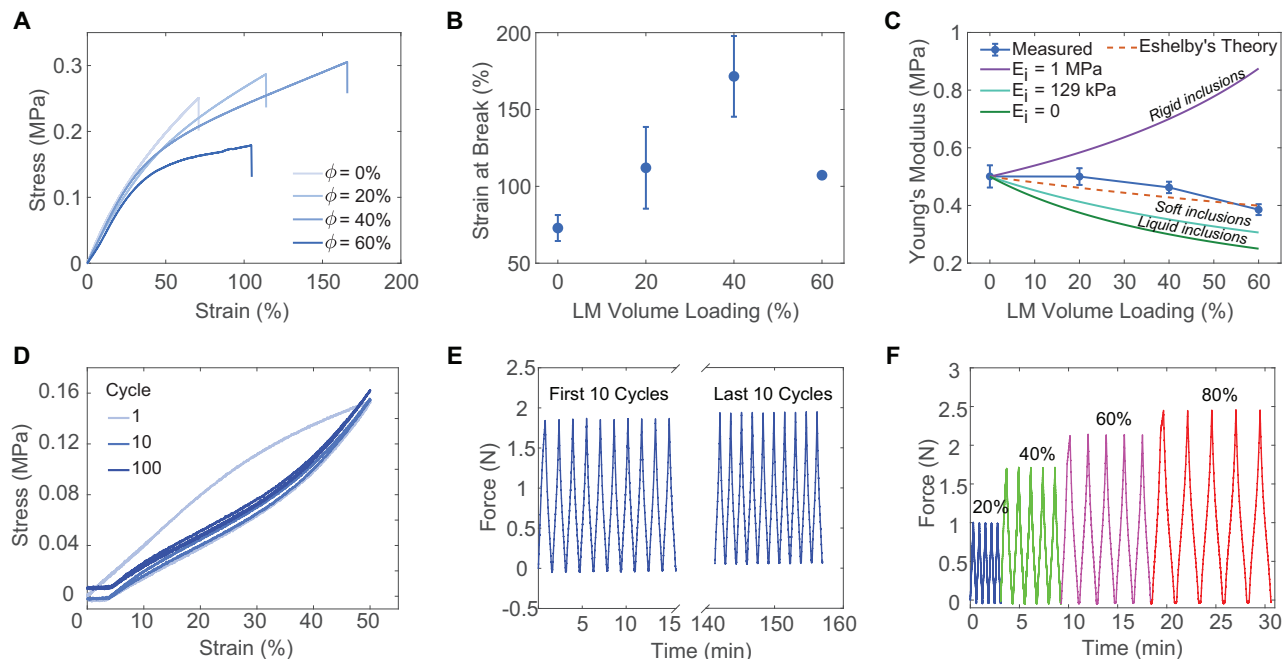


FIGURE 2 | Mechanical properties of S-LMEC. (A) Representative stress-strain curves for S-LMEC at various LM volume loadings. (B) Strain at break as a function of ϕ . (C) Young's modulus decreases with ϕ . The LM microdroplets act as soft inclusions according to Eshelby's Theory. Data in (B) and (C) is presented as mean $\pm$ SD ($n = 3$). (D) Stress-strain curves of $\phi = 40\%$ S-LMEC during cyclic testing of 100 cycles up to 50% strain ($n = 1$). (E) Corresponding change in force over time of $\phi = 40\%$ S-LMEC for 100 cycles up to 50% strain. (F) Change in force over time of $\phi = 40\%$ S-LMEC with five cycles at each 20% strain increment, up to 80% strain ($n = 1$).

significant degradation, softening, or loss of network integrity under cyclic fatigue.

In Figure 2F, the material was subjected to step-strain testing consisting of five loading-unloading cycles at progressive 20% strain increments up to 80% strain. As expected, the maximum force increased systematically with each strain step, from approximately 1 N at 20% strain to 2.5 N at 80% strain, with uniform peak forces maintained across all five cycles at each step. Additionally, the accumulation of residual strain remained low, rising from 0.97% following the 20% strain step to 8.49% after 80% elongation. To quantitatively evaluate dimensional restoration, the elastic recovery efficiency was defined as $R_e = \left(1 - \frac{\epsilon_{\text{residual}}}{\epsilon_{\text{applied}}}\right) \times 100\%$. The S-LMEC retained high elastic recovery across all deformation steps, exhibiting $R_e = 95.15\%$ at 20% strain ($\epsilon_{\text{residual}} = 0.97\%$) and maintaining $R_e = 89.39\%$ following severe 80% elongation ($\epsilon_{\text{residual}} = 8.49\%$), highlighting substantial recovery. Collectively, these quantitative metrics demonstrate that the S-LMEC exhibits a predictable, stable, and resilient response across wide operational deformation ranges.

2.2 | Thermal Conductivity Measurements

The thermal conductivity of the S-LMEC at various ϕ was determined using the transient plane source (TPS) method (Figure 3A). Here, a hot disc is placed in between two homogeneous samples and acts as both the sensor and heat source for the measurement. The unfilled RTV567 silicone elastomer has a measured $k = 0.172 \text{ W m}^{-1} \text{ K}^{-1}$, which is comparable to other silicones. At $\phi = 20\%$, the addition of LM microdroplets has a mild effect on the thermal

conductivity, increasing it by 20%. As more LM is added to the system, k increases exponentially, up to $1.9 \text{ W m}^{-1} \text{ K}^{-1}$ at $\phi = 60\%$, which is an 11 $\times$ increase compared to the unfilled elastomer. The data was compared to Bruggeman effective medium theory (EMT) [43, 45] using values for the thermal conductivity of the EGaIn microdroplets $k_p = 26.4 \text{ W m}^{-1} \text{ K}^{-1}$ [46], RTV567 silicone matrix $k_m = 0.172 \text{ W m}^{-1} \text{ K}^{-1}$, and depolarization factor $L = 1/3$ for spherical particles, to determine the composite thermal conductivity k_c :

$$\left(\frac{k_p - k_c}{k_p - k_m}\right) \left(\frac{k_m}{k_c}\right)^L = 1 - \phi \quad (2)$$

The measured values for the thermal conductivity of the S-LMEC are in good agreement with the EMT model. This demonstrates the ability to significantly enhance the thermal conductivity of a traditionally thermally insulating material with the addition of LM microdroplets. In addition, mechanical properties of the S-LMEC are preserved due to the liquid state of the inclusions.

2.3 | Electrical Properties Characterization

We investigated the dielectric properties of the S-LMEC as a function of ϕ . Results from measuring the effective dielectric permittivity (ϵ_r) of the material are presented in Figure 3B. These measurements were taken at a frequency of 1 kHz and potential bias of 1 V. It can be seen that ϵ_r increases exponentially with ϕ , resulting in a 9.6 $\times$ increase from the unfilled silicone to $\phi = 60\%$. Concurrently, the dielectric loss tangent ($\tan \delta$) remains low across all compositions ($\tan \delta < 0.025$, Table S2), indicating that the addition of LM enhances polarization without introducing

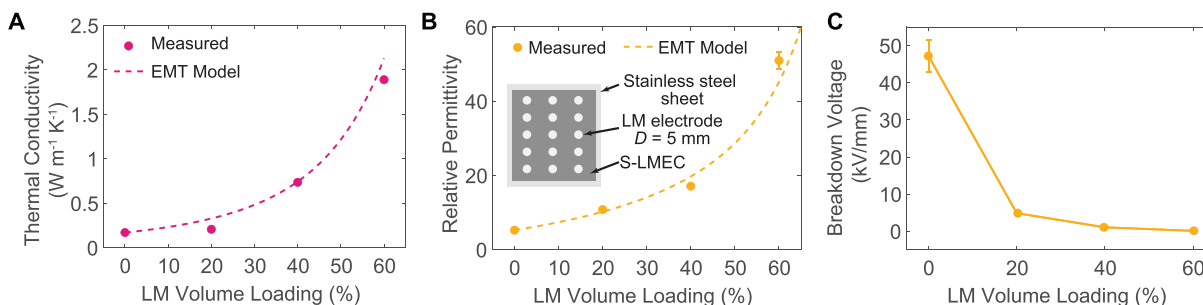


FIGURE 3 | Thermal and electrical properties of S-LMEC. (A) Thermal conductivity of the material increases with ϕ . The dashed line is a theoretical fit with the Effective Medium Theory model ($n = 3$). (B) Relative permittivity increases with ϕ , inset schematic shows the testing setup ($n = 10$). (C) Electric breakdown strength shows a significant decrease with ϕ ($n = 15$). Data is presented as mean $\pm$ SD and error bars not visible are smaller than the data points.

significant dielectric dissipation. These results were compared to EMT using a model developed by Nan et al. [47]

$$\epsilon_{rc} = \epsilon_{rm} \frac{1 - 2\alpha + 2\phi(1 + \alpha)}{1 - 2\alpha - \phi(1 + \alpha)} \quad (3)$$

in which ϵ_{rc} and ϵ_{rm} are the dielectric constants of the composite and matrix, respectively. The dimensionless factor α is associated with the diameter of the LM droplets, in which smaller droplets correspond to larger α . Here, $\alpha = 0.057$ based on previous work done by Pan et al. [23]. Fitting the measured data to Equation (3) demonstrates that it is in good agreement with the EMT model, and that the effect of ϕ on ϵ_r is accurately predicted.

To further examine the dielectric properties of the S-LMEC, measurements on the dielectric breakdown strength (E_b) as a function of ϕ were performed (Figure 3C). The Weibull distributions are presented in Figure S5, and the parameters are summarized in Table S3. Initially, the unfilled elastomer demonstrated an E_b of approximately 47 kV/mm. Increasing ϕ results in a dramatic 99.7% decrease in E_b at $\phi = 60\%$. This degradation occurs due to high internal electric field concentrations present in the thin film (≈ 330 – 360 μ m, Figure S4 and Table S1) due to the presence of LM droplets with droplet diameters of approximately 25–30 μ m. To quantify the microstructural uniformity, size distribution analysis was performed (Figure S1–S3), revealing a relatively narrow distribution with a standard deviation below 20%.

This highly controlled droplet uniformity plays a vital role in dictating the predictable and repeatable bulk performance of the S-LMECs. Mechanically, avoiding a broad, polydisperse distribution prevents the formation of relatively large LM inclusions or uncontrolled macro-clusters, which typically act as structural defects and premature stress-concentration sites during deformation. Furthermore, from a thermal and dielectric standpoint, the narrow size distribution ensures consistent, distributed local electric field and heat-flux profiles across the film, preventing early localized thermal or dielectric breakdown failures often observed in highly heterogeneous, poorly controlled particulate composites. Nevertheless, as the average droplet size is relatively large (~ 25 μ m), the electrical pathways within the film become poorly insulated due to the coarse nature of the microstructure, thus allowing E_b to quickly saturate even at low LM volume loadings.

This phenomenon highlights a fundamental dielectric trade-off in S-LMECs; the addition of LM microdroplets yields significant enhancements in relative permittivity, but it causes a concurrent and severe reduction in E_b . While this reduction restricts the use of high-loading S-LMECs in high-voltage dielectric applications, it does not impede low-voltage electronic configurations. For a representative 2 mm thick tactile sensor ($\phi = 40\%$), the reduced E_b of 1.1 kV/mm corresponds to a physical breakdown limit of ~ 2.2 kV. As standard capacitive tactile sensing and soft robotic skin data acquisition systems operate at very low driving potentials (typically ≤ 5 V), the actual operating field remains several orders of magnitude below the breakdown threshold, ensuring reliable long-term operational stability within low-power electronic applications. However, long-term dielectric reliability under continuous cyclic bias, high-field charge accumulation dynamics, and electrical aging mechanisms remain important subjects for future investigation.

Due to the presence of a passivating gallium oxide shell surrounding each LM droplet, the S-LMEC remains electrically insulating. A simple and rapid way to generate conductivity is to rupture the LM droplets by mechanically sintering the composite to form percolating networks [48]. Here, electrical traces were sintered on cast S-LMEC samples using an embossing tool and the resistance was measured with a handheld multimeter (Figure S6A). The traces did not return a resistance measurement and remained electrically insulating despite the application of mechanical force. LMECs made from traditional silicones such as Sylgard 184 ($E = 1.3$ – 2.9 MPa) [49] can be made electrically conductive after applying localized pressure, however, other silicones that are much softer, such as Ecoflex ($E = 0.125$ MPa) [50] and RTV567 ($E = 0.5$ MPa), show an inability to form percolating LM networks when mechanically sintered [51] (Figure S6B, Supplementary Information). Future work can be aimed at creating electrically conductive S-LMEC through the addition of conductive fillers such as silver flakes [52, 53].

2.4 | Thermal Stability and Degradation Behavior of S-LMECs

Thermogravimetric analysis (TGA) was conducted to verify the composition and evaluate the thermal stability of the S-LMEC at different ϕ . To isolate the degradation behavior of the polymer

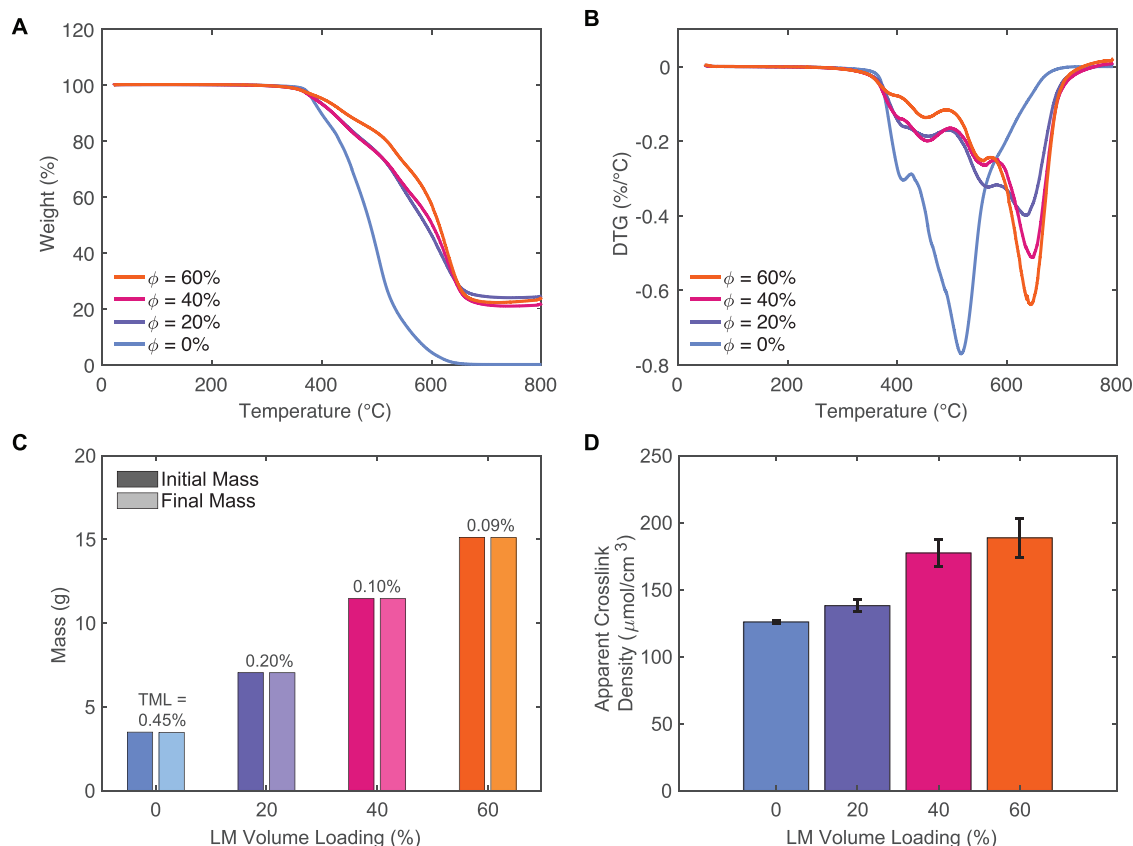


FIGURE 4 | Thermal and chemical stability behavior. (A) Normalized TGA curves of S-LMEC ($n = 1$). (B) First derivative of normalized TGA curves in (A). (C) Total mass loss (TML) before and after vacuum chamber testing ($n = 1$). (D) Apparent crosslink density results from swelling experiments. Data is presented as mean $\pm$ SD ($n = 3$).

phase from the high mass fraction of nonvolatile LM, the normalized data (calculating weight loss relative to the silicone mass) is presented in Figure 4A, and the raw data is provided in Figure S7. All samples were heated to 800°C and experienced apparent weight loss after 300°C. The residual material after TGA increases in S-LMEC with the addition of LM. The unfilled elastomer undergoes rapid degradation between 300°C and 650°C, however, samples with LM experienced the onset of degradation at similar or slightly higher temperatures. A 5% weight loss (relative to the polymer fraction) occurred at 381.96°C for the sample at $\phi = 0\%$, and 389.86, 386.16, and 402.76°C for $\phi = 20\%$, 40%, and 60%, respectively. For context, we compare our results to fluoroelastomer (FKM) materials, which are known for their high temperature resistance. Unfilled FKM and FKM-LM 40 vol% composites show a 5% weight loss in the temperature range 415°C–435°C, indicating no major alteration to the FKM degradation [54]. Consistent with these findings, embedding LM into space-grade RTV567 does not interfere with the underlying thermal stability of the polymer, as evidenced by the minor changes in normalized degradation profiles.

Furthermore, the first derivative of the TGA curves, called the Derivative Thermogravimetry (DTG) curves are shown in Figure 4B, which demonstrate how the rate of thermal degradation ($-dw_s/dT$) changes as a function of temperature. Various peaks can be seen in these DTG curves, which correspond to different thermal degradation mechanisms that RTV silicones typically undergo during TGA. These complex mechanisms can

TABLE 1 | Maximum rates of degradation of S-LMEC samples.

ϕ	Temperature (°C)	$-dw_s/dT$	Weight (%)
0	516.03	0.77005	28.491
20	635.36	0.39859	32.406
40	645.59	0.51135	28.957
60	642.65	0.63817	31.508

occur simultaneously and have been described in previous studies [55–57]. All samples show minimal rates of degradation below 300°C. Once the temperature exceeds 300°C, there is a rapid decomposition until the maximum thermal degradation rate is reached. Beyond this point, the samples degrade slowly until they reach $\approx 700^\circ\text{C}$. The maximum rate of degradation is lower in S-LMEC than in the unfilled silicone and increases as ϕ is increased (Table 1). While the unfilled elastomer decomposes completely, the normalized profiles for the S-LMECs stabilize to a constant plateau of $\sim 20\%$ – 25% residual mass between 650°C and 800°C. This plateau indicates that the presence of LM microdroplets alters residual mass formation during thermal decomposition. Rather than asserting specific reaction pathways, detailed microstructural, elemental, and chemical characterization of the solid residue (SEM/EDS, FTIR, Raman, and XPS) alongside evolved gas analysis (TGA-MS) remains essential future work to identify the exact compositional species and mechanisms

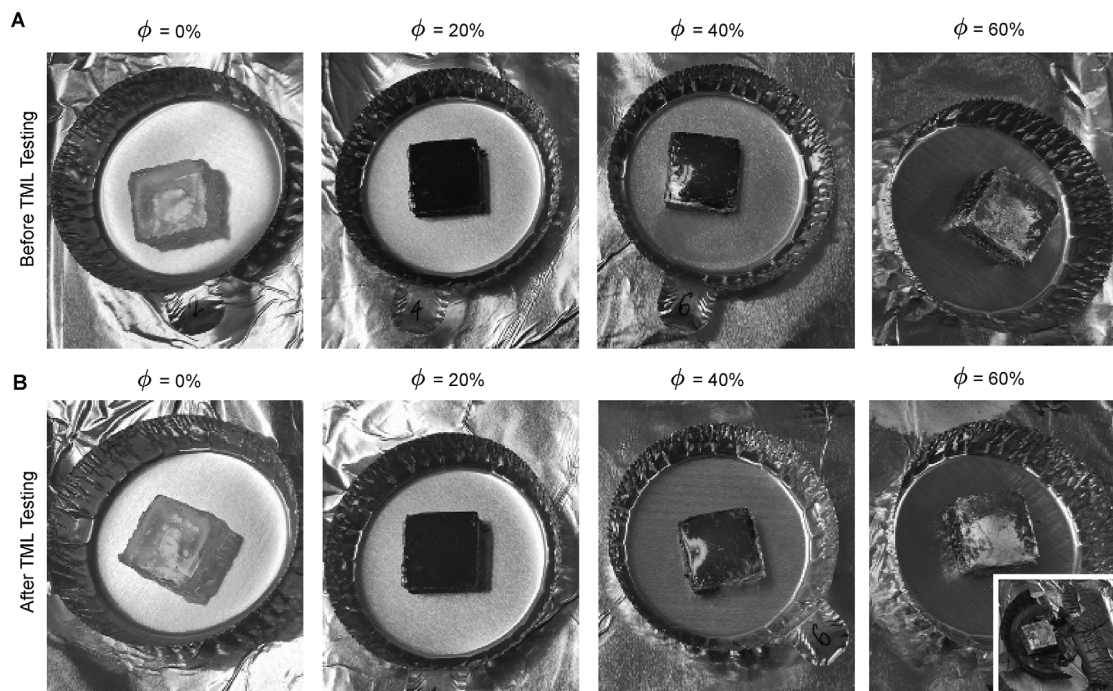


FIGURE 5 | Sample images from Total Mass Loss (TML) experiments. Photographs of $\phi = 0\%$ – 60% samples (A) before TML testing, and (B) after TML testing ($n = 1$ for each LM volume loading). Inset: LM spread on the outer surface of a $\phi = 60\%$ S-LMEC during sample preparation resulted in gallium embrittlement of the aluminum dish from an earlier $\phi = 60\%$ sample run.

governing this residual mass alteration. Collectively, these TGA results demonstrate that LM can be integrated into space-grade silicones to yield high-temperature, multifunctional composites without degrading matrix performance.

2.5 | Volatile Release and Outgassing Characteristics

Outgassing measurements were performed on the S-LMEC samples at NASA Marshall Space Flight Center to assess its potential for space applications. The total mass loss (TML) of the sample was measured after being exposed to a vacuum environment ($\leq 5 \times 10^{-5}$ torr) at 100°C for 24 h. Due to physical hardware and configuration constraints of the testing facility's vacuum chamber setup at the time of measurement, a full evaluation of the TML, Collected Volatile Condensable Materials (CVCM) percentage and Water Vapor Regained (WVR) according to ASTM E595 standards could not be completed [58]. S-LMEC with $\phi = 0\%$ – 60% LM loading were tested and the mass measurements were taken before and after the test (Figure 5A,B) using a high-precision balance (resolution ± 0.01 mg), and the TML was calculated as the percentage of initial sample mass lost during the test. These results are plotted in Figure 4C, which show that all materials exhibit low TML ($\leq 1.00\%$), indicating that the addition of LM does not significantly affect the outgassing properties of RTV567. The TML is highest at 0.45% for $\phi = 0\%$ and gradually decreases with $\phi = 60\%$ showing a TML of 0.09% . The lower volatility of S-LMEC at higher ϕ is likely due to the relatively high mass of LM compared to silicone, and diffusion-limited volatile transport. However, higher ϕ increases the likelihood of flaking and residual material coming off, causing gallium to infiltrate the surrounding aluminum dish as seen in one sample (Figure 5 inset).

Gallium poses a well-known integration risk due to liquid metal embrittlement (LME), rapidly penetrating grain boundaries upon direct physical contact with structural metals, particularly aluminum alloys [59]. This key limitation of the S-LMEC presents a significant aerospace integration challenge, as spacecraft structures and electronic enclosures rely heavily on metallic components vulnerable to LME. While potential mitigation strategies include replacing sensitive structural components with LME-resistant materials, such as titanium or applying protective interface barrier coatings to adjacent aluminum assemblies, these integration approaches remain unverified for spaceflight environments. Furthermore, microstructural containment methods like surface functionalization to enhance droplet-matrix adhesion, core-shell microencapsulation, or applying an outer barrier elastomer layer to physically isolate gallium-based LM during mechanical deformation, should be systematically evaluated. Consequently, rigorous experimental testing and long-term reliability validation under spaceflight conditions are required in future studies to establish the effectiveness of these protection strategies and ensure the physical containment of liquid gallium. While this preliminary TML testing results indicate a critical initial step for space-grade compliance, a comprehensive discussion regarding the broader environmental operational stressors required for full aerospace qualification is detailed in Section 2.9.

2.6 | Crosslink Density of S-LMEC Polymer Network

Solvent extraction and swelling experiments were performed to evaluate the nature of the S-LMEC network at various ϕ (Figure 4D and Figure S8). Gel fraction was calculated as the percent of the polymer remaining post swelling ($f_{\text{gel}} = m_{\text{dry}}/m_0$)

while the crosslink density was calculated with the Flory–Rehner equation [60].

$$\gamma_e = -\frac{1}{2V_s} \frac{\ln(1 - \phi_e) + \phi_e + \chi\phi_e^2}{\phi_e^{1/3} - \frac{\phi_e}{2}} \quad (4)$$

Here, the apparent crosslink density (γ_e) is calculated with the molar volume of the solvent (V_s) the volume fraction of the polymer (ϕ_e), calculated with the weight of dry (m_{dry}) and swollen ($m_{swollen}$) polymer along with the density of the polymer (ρ_{PDMS}) and solvent ($\rho_{solvent}$).

$$\phi_e = \frac{\frac{m_{dry}}{\rho_{pdms}}}{\frac{m_{dry}}{\rho_{pdms}} + \frac{m_{swollen} - m_{dry}}{\rho_{solvent}}} \quad (5)$$

The final variable required is the Flory–Huggins parameter χ . This can be calculated with the molar volume of the polymer (V_1), temperature (T), the gas constant (R), and Hildebrand solubility parameters of both polymer (δ_1) and solvent (δ_2). The Hildebrand solubility parameters of PDMS and hexanes are very close, so χ can be taken as zero for this calculation [61].

$$\chi = \frac{V_1}{RT} (\delta_1 - \delta_2)^2 \quad (6)$$

We have adjusted the Flory–Rehner equation here to solve for molar density of crosslinks (γ_e) rather than chains (ν_e). This conversion relies on an assumption of the number of chains at each crosslink site (f). We conservatively assumed the crosslinks are formed from four chains in this calculation, resulting in the factor of two in Equation (4). The true value may be less which would result in our calculations being an underestimate of apparent crosslink density.

$$\nu_e = \frac{f * \gamma_e}{2} \quad (7)$$

Our results show minimal extractable components, indicating good curing of the polymer system. The slight decrease in gel fraction with increasing ϕ is likely due to errors arising from the removal of small amounts of LM over the course of swelling, which would appear as unbound polymer. This loss is caused by the swelling of the polymer network while LM does not swell or dissolve in hexane resulting in more mobility for the LM filler. This is especially true of the LM at the surface of highly filled samples. This theory is supported by the increase in error with increased ϕ (Figure S8). The calculated apparent crosslink density may be similarly affected by the removal of small amounts of LM over the course of the experiment; however, strong interactions are also known to take place between the passivating gallium oxide layer surrounding the LM and pendant hydroxy groups which are present in this polymer system and may explain some of the measured increase in crosslink density (Figure 4D) [62]. Furthermore, the Flory–Rehner equation is for an ideal polymer system and will result in an overestimate of polymer crosslinks when fillers are present, as they do not swell. We performed a simple correction for this by removing the mass of LM in filled samples from the dry and swollen weights measured during swelling tests, but the filler will still affect the calculated values. We have only taken these values as a comparison between similar

systems, and they should not be extended as comparisons to other systems.

2.7 | Heat Dissipation Demonstration

The addition of LM microdroplets into the RTV567 elastomer matrix enables greater functionality beyond serving as a silicone sealant. Here, the ability of the S-LMEC to dissipate heat is evaluated through proof-of-concept thermal management demonstrations. To evaluate the transient and steady-state thermal behavior of the S-LMEC during electronic operation, real-time transient temperature profiles and surface thermal distributions were recorded using a high-resolution infrared (IR) camera (Figure 6). As an initial visual demonstration of localized thermal spreading, a patterned composite made of unfilled RTV567 surrounding a NASA logo composed of $\phi = 40\%$ S-LMEC was fabricated (Figure 6A). A convective heat source (heat gun) was used to apply heat to the front surface for 30 s and subsequently turned off to allow passive cooling to room temperature (Figure 6B). The unfilled silicone region reached a maximum average temperature of 75°C, whereas the NASA logo reached a peak temperature of 58°C, a 17°C surface temperature difference under identical convective heating exposure. Infrared images captured during the test illustrate that the NASA logo remained substantially cooler compared to the surrounding material due to the presence of LM microdroplets in the composite (Figure 6C and Video S2).

To further demonstrate potential utility as a thermal interface substrate under controlled electrical power input, a representative high-power LED mounted on a copper lead architecture was evaluated. The assembly was mounted onto either an unfilled RTV567 substrate or a $\phi = 40\%$ S-LMEC film (2 mm thickness) with a standardized droplet of LM (~10 μ L) between the LED and the substrate to ensure uniform, low thermal contact resistance across all trials. During a short-term activation test (1 min), rapid heat generation at the LED junction caused the surface temperature of the unfilled RTV567 system to rise sharply to a peak of ~59°C (Figure 6D). In contrast, the high-thermal conductivity LM pathways in the $\phi = 40\%$ S-LMEC film facilitated rapid lateral heat spreading, reducing the peak transient temperature to 48°C.

To evaluate steady-state thermal trends under extended operation, the samples were monitored over a 5-min continuous heating window (Figure 6E). Under these testing conditions, the unfilled RTV567 substrate reached a steady-state plateau of approximately 80°C. Conversely, the $\phi = 40\%$ S-LMEC substrate stabilized at a steady-state operating temperature of ~55°C, representing a ~25°C temperature reduction at the monitored surface. Based on one-dimensional heat conduction estimates ($R_{th} = d/(k \cdot A)$, where R_{th} is the conductive thermal resistance, d is the substrate thickness, k is the bulk thermal conductivity, and A is the heat transfer surface area), increasing the LM volume loading to $\phi = 40\%$ ($k \approx 0.73 \text{ W m}^{-1} \text{ K}^{-1}$) yields a ~4.2× reduction in substrate conductive thermal resistance compared to unfilled RTV567 ($k \approx 0.172 \text{ W m}^{-1} \text{ K}^{-1}$) for an equivalent film geometry. This operating range (25°C to 85°C) corresponds to standard internal qualification temperature limits for spacecraft electronics and instrumentation (e.g. NASA-STD-7002B). By suppressing the peak operating temperature, the S-LMEC maintained the LED junction well below the critical thermal limit. Furthermore,

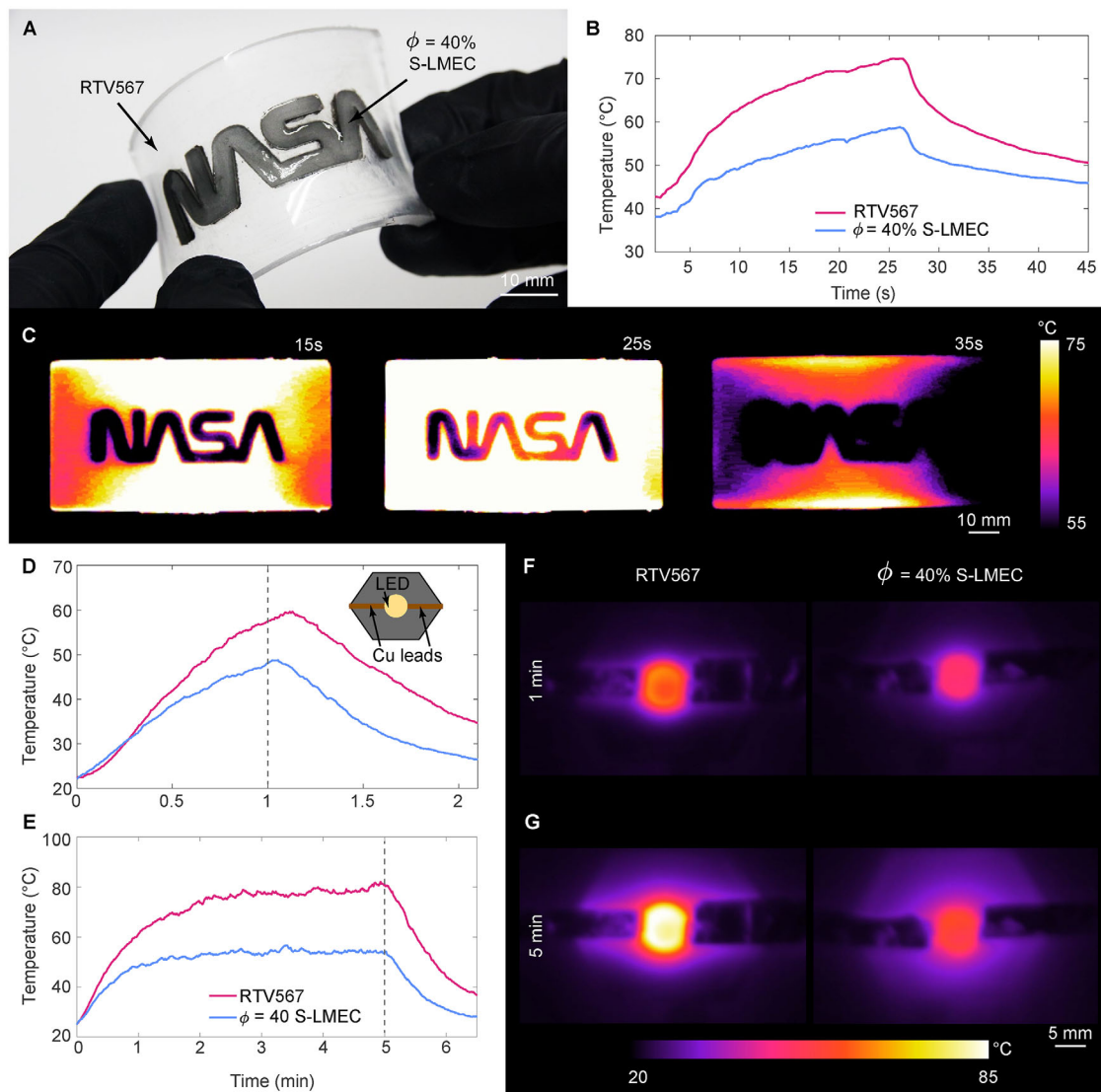


FIGURE 6 | Heat dissipation demonstration of S-LMEC. (A) Photograph of the sample with NASA logo composed of $\phi = 40\%$ S-LMEC and the surrounding material made from unfilled RTV567 silicone. (B) Temperature vs. time curves for $\phi = 40\%$ S-LMEC and RTV567 sections of the material. (C) IR images of the material as heat is applied with a heat gun and followed by removal to cool it down. (D) Real-time transient temperature profiles comparing the unfilled RTV567 matrix and the $\phi = 40\%$ S-LMEC during a short-term 1 min operational window. Inset shows a schematic of the test setup with a high-power LED connected with copper leads. (E) Long-term thermal stability and steady-state temperature curves over a 5 min continuous operation window. (F, G) Representative high-resolution IR thermographs tracking the localized heat-spreading behavior and thermal gradients of the substrates at the 1 and 5 min operational marks. $n = 1$ for both demonstrations, temperature measurement uncertainty is $\pm 2^\circ\text{C}$ based on FLIR A700 IR camera calibration.

the S-LMEC displayed an accelerated thermal response time, mitigating sharp localized thermal gradients within the first 60 s of operation (Video S3). The corresponding IR images taken at the 1-min (Figure 6F) and 5-min (Figure 6G) intervals highlight the potential of S-LMECs as efficient candidate materials for passive thermal management in aerospace subsystems.

2.8 | Capacitive Tactile Sensor for Object Recognition

To evaluate the potential of the S-LMEC sensors for wearable electronics and soft robotics, we systematically characterized their electromechanical performance under cyclic compressive

loading and integrated them into a glove. By applying copper electrodes on either side of a thin S-LMEC slab, changes in capacitance can be measured when the device is compressed. This can be utilized as a tactile sensor for monitoring human-object interactions during extravehicular activities and human-robot collaboration in space by providing real-time force and contact feedback. The mechanical response of a $\phi = 40\%$ S-LMEC sample exhibits a characteristic elastomeric behavior, showing increasing hysteresis loops with compressive strain levels ranging from 10% to 50% (Figure 7A). The sensor's capacitive response directly mirrors this strain dependency, as evidenced by the synchronized increase in normalized capacitance ($\Delta C/C_0$) reaching up to ~ 9 at 50% strain (Figure 7B). Continuous cyclic testing across stepped strain amplitudes confirms the excellent real-time

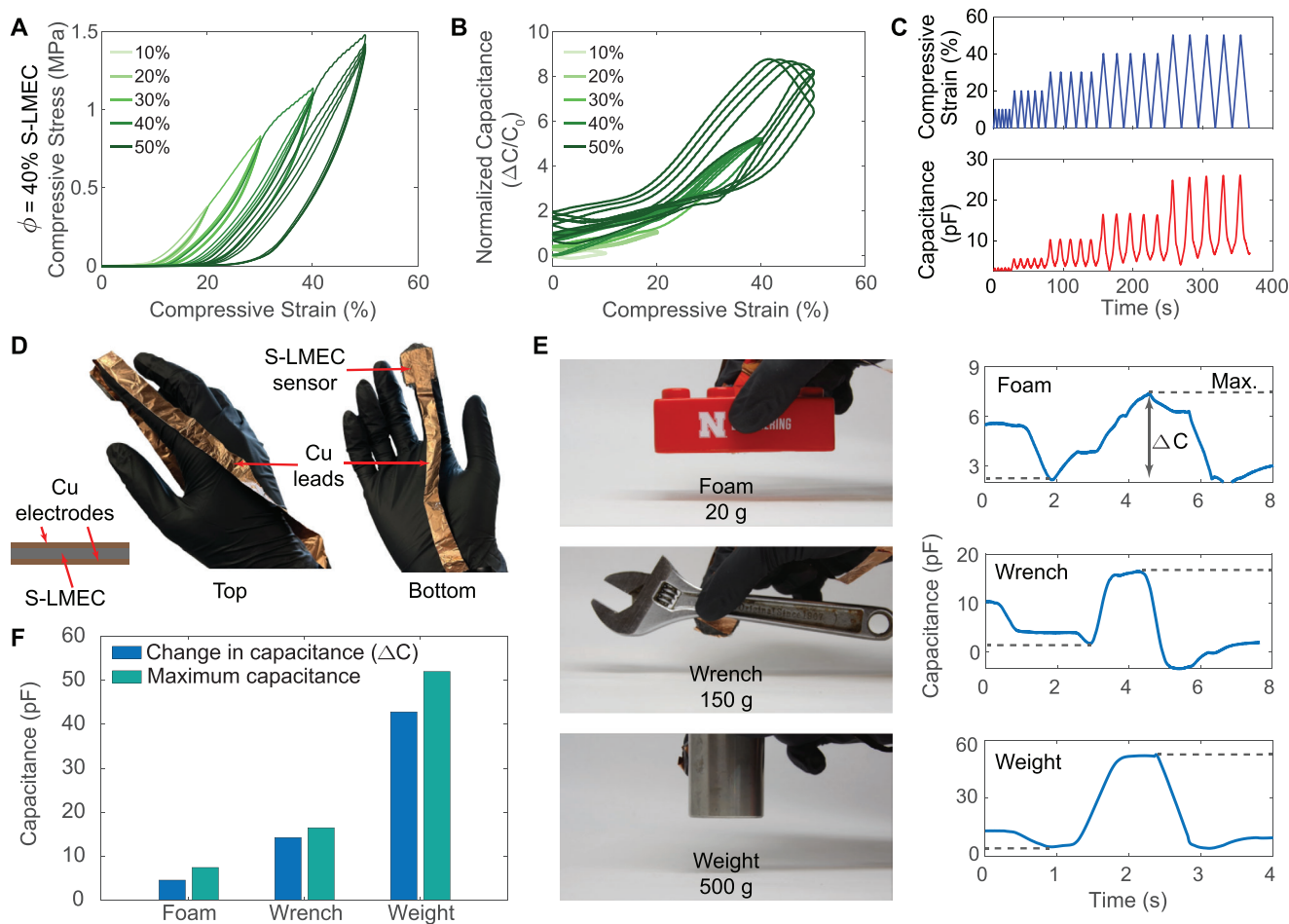


FIGURE 7 | Electromechanical behavior of S-LMEC and application as a soft capacitive sensor. (A) Compressive stress-strain curves of a $\phi = 40\%$ S-LMEC under cyclic loading up to 50% strain. (B) Corresponding normalized capacitance as a function of compressive strain. (C) Time-dependent cyclic performance showcasing the relative change in stepped compressive strain profile (top, blue) and real-time capacitance response (bottom, red). (D) Photographs of glove integrated with an S-LMEC sensor, schematic shows a cross-sectional view of sensor architecture sandwiched between copper (Cu) electrodes. (E) Demonstration of the tactile glove grasping and lifting objects of varying masses: a foam block (20 g), a wrench (150 g), and a cylindrical metal weight (500 g), with corresponding real-time capacitance profiles tracking the grasp duration on the right. Dashed lines illustrate the baseline and peak points defining the capacitive shift (ΔC). (F) Change in capacitance and maximum capacitance calculated across the three distinct object manipulation trials. $n = 1$ for all the data presented in this figure.

responsiveness, signal stability, and high repeatability of the sensor without noticeable baseline drift (Figure 7C).

To demonstrate a practical application, an S-LMEC sensor was mounted onto the index finger of flexible glove using copper (Cu) leads and electrodes (Figure 7D). The smart glove was utilized to grasp three objects of vastly different masses, a lightweight foam block (20 g), an intermediate-weight wrench (150 g), and a heavy metal weight (500 g) as shown in Figure 7E and Video S4. Real-time capacitance profiles uniquely distinguish each object through both transient deformation signatures (initial squeezing artifacts), and distinct peak plateaus (Figure 7E, right panels). A summary of both the overall change in capacitance (ΔC) and the maximum absolute capacitance were plotted in Figure 7F, both of which scale monotonically with the object weight. There is a $\sim 10\times$ difference in maximum capacitance between the foam block and metal weight, validating the S-LMEC sensor as a real-time weight and contact force sensor for robotic manipulation.

2.9 | Spaceflight Qualification and Limitations

While the short-term thermal stability, crosslinking integrity, and baseline outgassing compliance of the S-LMECs are highly promising, full aerospace qualification requires evaluating the material's long-term resilience under realistic space conditions. Future work must evaluate the CVC and WVR in addition to TML according to the appropriate test parameters outlined in ASTM E595 in order to fully qualify the S-LMEC to NASA standards for spaceflight materials [58]. It will also be necessary to map the S-LMEC performance under prolonged exposure to low Earth orbit (LEO) radiation and atomic oxygen according to evaluation frameworks like ASTM E2089 to ensure the LM-elastomer interface remains stable. Additionally, long-term environmental cycling under hardware testing frameworks such as NASA-STD-6016 (typically spanning -120°C to $+120^\circ\text{C}$) is necessary to monitor how repeated thermal cycling affects microstructural integrity. In this context, the space-grade silicone

matrix (Momentive RTV567) retains its elastomeric properties continuously from -115°C to $+205^{\circ}\text{C}$ (and up to $+260^{\circ}\text{C}$ for short durations). Furthermore, while bulk EGaIn melts at $\sim 15.5^{\circ}\text{C}$, dispersing EGaIn into discrete microdroplets within the elastomeric matrix suppresses crystallization via deep liquid supercooling, maintaining soft compliance, mechanical flexibility, and liquid thermal transport pathways down to temperatures as low as -70°C to -85°C [24]. Even if extreme sub-zero conditions induce partial droplet crystallization below -85°C , the high network compliance of the surrounding silicone matrix prevents micro-cracking, with full liquid transport properties recovering upon thermal cycling above 15.5°C . Finally, the long-term effects of microgravity and mechanical fatigue life on high-density LM droplets must be systematically evaluated to bridge the gap between our laboratory metrics and flight-ready deployment in space applications.

3 | Conclusion

This work demonstrates that multifunctional, low-outgassing composites for potential space applications can be created by incorporating LM into space-grade RTV567 silicone. The S-LMEC system provides tunable combination of mechanical properties (high deformability and flexibility), and enhancements in thermal and dielectric behavior, supported by predictive modeling. The LM inclusions enhance the deformable properties of the RTV silicone by increasing the strain at break to $2.3\times$ while reducing the Young's modulus by 8%, as compared to the unfilled silicone. Cyclic testing also shows that the material exhibits a predictable, stable, and resilient response across a wide range of operational deformations. Further, the LM microdroplets do not alter the thermal stability of the space-grade elastomer, as evidenced by thermogravimetry and DTG curves, with negligible effects on the curing process of the silicone matrix. Swelling and outgassing experiments also indicate high degree of crosslinking and minimal residual volatiles ($<1\%$ TML). The improved thermal conductivity ($11\times$ higher) and stability at elevated temperatures enable enhanced thermal dissipation in S-LMEC, allowing the composite material to stay up to 25°C cooler than unfilled silicone. The electromechanical behavior of the S-LMEC also enables sensors for wearable electronics and soft robotics, and is implemented in a tactile glove for object manipulation. Furthermore, we demonstrated the versatility in manufacturing the S-LMEC through traditional molding approaches and DIW additive manufacturing for intricate designs and on-demand fabrication or assembly. Low-outgassing multifunctional materials, such as the S-LMEC, could expand the applications for silicones currently used in space, including powering soft robots, manufacturing electronics on-demand in long-duration missions, and repairing electronic devices and components.

4 | Experimental Details

4.1 | Materials

Gallium (Ga) was purchased from Rotometals and Indium (In) was purchased from Indium Corp. Eutectic gallium-indium (EGaIn) was made by combining 75% Ga and 25% In by weight and leaving overnight in an oven at 120°C to alloy. Momentive

RTV567 silicone was purchased from R.S. Hughes. Acetal (Delrin) was purchased from McMaster-Carr.

4.2 | Liquid Metal Composite Fabrication

The LM composites were fabricated by dispersing EGaIn in a two-part space-grade polydimethylsiloxane (PDMS; RTV567; Momentive Performance Materials Inc.). The PDMS was first prepared by combining part A and part B at a 1000:1 mass ratio and mixing in a planetary mixer (SpeedMixer DAC 400.2 VAC, FlackTek Inc), at 1500 RPM for 1 min and subsequently at 2000 RPM for 1 min. Bulk LM was then added to the PDMS at different volume loadings ($\phi = \text{volume}_{\text{LM}} \times 100 / \text{volume}_{\text{PDMS+LM}}$) and hand-mixed to break it into droplets. The mixture was placed into the planetary mixer again and mixed at 2300 RPM for 2 min. The uncured LM composite was then poured into molds or 3D printed before curing. Placing samples immediately into a pre-heated 80°C environment drives rapid thermal matrix gelation within minutes, locking the dense EGaIn droplets ($\rho \approx 6.25 \text{ g cm}^{-3}$) in place and suppressing gravity-driven sedimentation before crosslinking is completed, yielding uniform spatial particle distributions across all volume loadings (Figure S3).

Standard test specimens were cured at 80°C overnight ($\sim 12 \text{ h}$) in a pressure pot at 40 psi to remove air bubbles. However, samples made for swelling and outgassing tests were cured at 80°C for 1 day in a pressure pot at 40 psi and subsequently post-cured for 4 days in an oven at 80°C due to their larger geometries ($2 \text{ cm (L)} \times 2 \text{ cm (W)} \times 1 \text{ cm (H)}$), ensuring complete core network crosslinking and volatile/solvent extraction stability prior to testing.

To create samples for swelling experiments, square walls with dimensions of $2 \times 2 \times 1 \text{ cm}$ were 3D printed using a Formlabs Form 4 with High Temperature Resin V2. After printing, the molds were placed in isopropanol for 5 min to wash off excess resin. They were then dried, and the support material was removed from the parts. The molds were then cured at 80°C for 120 min in a Form Cure. Once fully cured, the molds were dipped in a quick-curing dental elastomer (Elite Double 32, Zhermack) and bonded to microscope glass slides (Amscope), which serve as removable bottoms of the mold for easy release of the samples after curing. The final mold assembly was cured for 10 min at 80°C . Uncured S-LMEC can then be poured into the molds and cured overnight in the pressure pot (followed by the 4-day oven post-bake). To remove the cured samples, the molds containing the S-LMEC were pulled off the glass slides, and a sharp blade was applied along the inner diameter to separate the material. The sample was then gently pushed out and excess LM was cleaned using Simple Green. This mold design ensures complete removal of the sample after curing without damage.

The composite as shown in the heat dissipation demonstration was fabricated by first casting unfilled RTV567 silicone in a custom mold made from acetal (Delrin). Delrin was selected as the mold material due to its low surface energy, allowing the composite to be easily removed once cured. After curing the RTV567 overnight at 80°C , a laser cutter (Epilog Mini) was used to cut a NASA worm logo in the center of the mold. The cut logo

was then carefully removed, and the space was filled with $\phi = 40\%$ S-LMEC. The composite was cured again at 80°C overnight and was subsequently removed from the mold.

4.3 | 3D Printing Liquid Metal Composite Thin Film

A direct ink write 3D printing system (NOVA, Voltera) was utilized to fabricate the thin film S-LMEC sample. The liquid ink was generated using similar methods outlined previously, however, the part A and B mass ratio was modified to 200:1. The ink was loaded on the printer and extruded onto a thin (0.127 mm) polycarbonate sheet (McMaster-Carr). The first and third layer consisted of unfilled RTV567 silicone, and the second layer is made from $\phi = 40\%$ S-LMEC. Each layer was cured in an oven at 120°C overnight before printing the next layer on top. The $\phi = 0\%$ and $\phi = 40\%$ inks were printed using 18 and 25 Ga syringe tips, respectively (SmoothFlow Tapered Dispense Tips, Nordson EFD). Toolpaths were generated using proprietary software associated with the 3D printer.

4.4 | Droplet Size Measurements

After mixing uncured S-LMEC, a small sample was placed on a microscope slide and examined under a Zeiss AxioZoom V16 stereo microscope. Optical micrographs were obtained and LM droplet diameters were analyzed using the “Measurement” tool in ImageJ. Each measurement for LM droplet sizes at $\phi = 20\%$, 40% , and 60% contains a minimum of 100 droplets.

4.5 | Mechanical Characterization

Tensile tests to determine the sample elastic modulus were performed on an Instron 5966 dual column universal testing machine with a 100 N load cell and a strain rate of $10\text{ mm} \cdot \text{min}^{-1}$. Bluehill Universal software was used to collect force and displacement data from the machine. Samples were held by pneumatically controlled grips with 250 N force capacity. Measurements were performed using dogbone samples scaled to 50% the size of ASTM D412A standard with width of 6 mm, length of 70 mm, and approximately 45 mm between the grips. For cyclic tensile tests, a sample was stretched up to 50% strain for 100 cycles, and another sample up to 80% for 5 cycles in 20% strain increments. Both samples were stretched at a displacement rate of $30\text{ mm} \cdot \text{min}^{-1}$. Dogbone samples were fabricated by curing the S-LMEC in Delrin molds at 80°C overnight in a pressure pot at 40 psi.

4.6 | Thermal Conductivity Measurements

The transient plane source (TPS) method was utilized to measure the thermal conductivity of the samples using a Thermtest MP-V. A hot disc with radius of 6.4 mm was placed between two homogeneous samples of area 1600 mm^2 and thickness of 5 mm to ensure even heating and reduce boundary effects. The samples and hot disc were then placed between two 10

mm thick slabs of silicone, and a 500 g mass was placed on top to ensure good contact between the hot disc and samples. Optimal test conditions were determined by initially performing a parametric sweep of power and time. Samples were tested at power settings of 0.037, 0.031, 0.031, and 0.079 W for $\phi = 0\%$, 20% , 40% , and 60% , respectively. All samples were heated for 5 s except $\phi = 40\%$ samples, which were heated for 10 s.

4.7 | Electrical Characterization Measurements

To study the electrical properties of the S-LMEC, thin films at each ϕ were cast onto stainless steel sheets using a thin film applicator and cured at 80°C overnight. A mask containing 15 circular electrodes with diameters of 5 mm in a 5×3 array was laser-cut on adhesive paper. LM electrodes were then sprayed onto the surface of the films using an air spray gun. The capacitance and dissipation factor ($\tan \delta$) at each electrode were measured using a benchtop LCR meter (894, BK Precision) at a frequency of 1 kHz and potential bias of 1 V across $n = 10$ electrodes per loading condition, yielding low dielectric loss tangents across all loadings (Table S2). The dielectric permittivity was subsequently calculated from capacitance and film thickness for these $n = 10$ sites. Breakdown strength was determined using a high voltage amplifier (Model 20/20C, Trek), which amplified the power from a source meter (2461, Keithley) with a gain of 2000. Voltage was ramped at 5 V s^{-1} until the system shorted across all $n = 15$ electrodes for each volume loading to extract Weibull statistical distribution parameters (η, β).

For electrical conductivity measurements, S-LMEC with $\phi = 40\%$ was cast into custom molds to create samples with thickness of 1.5 mm. An embossing tool was utilized to manually apply mechanical force and sinter LM droplets to form electrical traces on each sample. The resistance of each sample was measured using a handheld multimeter (Milwaukee Tool) to determine if the sample was conductive.

4.8 | Thermogravimetric Analysis

Samples between 20 and 30 mg were measured in triplicate with a TA TGA550 in a platinum pan. All tests were performed at a $10^\circ\text{C min}^{-1}$ ramp rate to 800°C under a nitrogen atmosphere.

4.9 | Swelling Experiments

To determine network characteristics, samples ($2 \times 2 \times 1\text{ cm}$, individual volume of 4 cm^3) were weighed and then submerged in 200 mL of hexane, maintaining a solvent-to-sample volume ratio of 50:1 for 72 h with the solvent replaced every 24 h. After recording the swollen mass, samples were placed in a 110°C oven for 24 h to remove any residual solvent and weighed again while hot. Three samples ($n = 3$) were evaluated at each ϕ . All masses were corrected for the loading of liquid metal to isolate elastomeric network swelling properties (i.e., $m_{\text{dry}} = m_{\text{dry},0} - m_{\text{LM}}$ and $m_{\text{swollen}} = m_{\text{swollen},0} - m_{\text{LM}}$).

4.10 | Outgassing Experiments

Unfilled RTV567 silicone and S-LMEC samples with dimensions of $2 \times 2 \times 1$ cm were prepared to evaluate their outgassing characteristics for use in vacuum environments. Samples with $\phi = 0\%$, 20% , 40% , and 60% were tested in a thermal vacuum bakeout chamber at NASA Marshall Space Flight Center under a vacuum level of $\leq 5 \times 10^{-5}$ torr and a temperature of 100°C for 24 h. The collector surface was maintained at 25°C .

4.11 | Heat Dissipation Demonstrations

Samples were placed on a glass sheet and exposed to a heat gun for 20–30 s until the surface temperature reached 60°C – 70°C to observe the transient heat dissipation behavior of S-LMEC. The printed thin film was adhered to the glass sheet with tape during the demonstration. The heat gun was then turned off to allow the sample to cool until it reached room temperature. To evaluate the steady-state thermal response, high-power LEDs were placed on top of 2 mm thick slabs of $\phi = 0$ and 40% S-LMEC. Copper tape was used to interface the LEDs with the power supply, set to generate 5 V and 0.3 A. A standardized droplet of LM (~ 10 μL) was added between the LED and S-LMEC to reduce the thermal contact resistance and to facilitate a direct transfer of heat from the heatsink pad and to the RTV567 silicone or the S-LMEC. The LEDs were powered on for 1 and 5 min, allowing to cool down to room temperature after powering off. An infrared camera (A700, FLIR; accuracy $\pm 2^\circ\text{C}$) was utilized to record videos during the demonstrations ($n = 1$) and collect thermal data. The camera surface emissivity was set to a constant value of $\epsilon = 0.95$ for all measurements, corresponding to the standard emissivity of the silicone polymer matrix. As the LM microdroplets are fully encapsulated within the opaque RTV567 elastomer matrix, the overall surface radiative properties remain governed by the silicone outer layer, ensuring consistent emissivity across both unfilled RTV567 and S-LMEC composite formulations.

4.12 | Capacitive Sensor Demonstration

The capacitive sensors were made from S-LMEC slabs of $\phi = 0$ and 40% S-LMEC with thicknesses of 2 mm cast using molds. After curing, copper tape was applied to either side of the slabs as electrodes and as leads to interface with the digital multimeter (Keithley DMM6500, Tektronix). The samples were placed under a compressive load of 5 cycles with increasing strain up to 50% , at a displacement rate of $5 \text{ mm} \cdot \text{min}^{-1}$ using an Instron 5966 mechanical testing machine with a 2 kN load cell. The change in capacitance was measured using the DMM. To integrate the capacitive sensor with the glove and to interface with the copper tape, a silicone glue (Silpoxy, Smooth-On) was used. Additional silpoxy was then applied to top side of the sensor to securely attach it to the glove. Three different items (foam block, wrench, and weight) were picked up while wearing the sensor, and the capacitive response was recorded using the DMM. A symmetric moving average filter was used to smooth the signal.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the supplementary material of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File 1: admt71422-sup-0001-SuppMat.pdf.

Supporting File 2: admt71422-sup-0002-VideoS1.mp4.

Supporting File 3: admt71422-sup-0003-VideoS2.mp4.

Supporting File 4: admt71422-sup-0004-VideoS3.mp4.

Supporting File 5: admt71422-sup-0005-VideoS4.mp4.