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AUTONOMIC RESTORATION OF CONDUCTIVITY IN LI-ION BATTERIES AND HIGHLY CONDUCTIVE MICROELECTRONIC CIRCUITS

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ABSTRACT

A variety of complex damage mechanisms in Li-ion batteries and microelectronics can lead to a significant loss of conductivity, and eventual system failure. For Li-ion batteries, cracking, deterioration, and electrochemical pulverization occur during the massive volume changes associated with the intercalation/deintercalation of Li^+ ions during charge and discharge. As this damage accumulates, there is a significant degradation of the efficiency, and eventually failure of the battery. In microelectronics, mechanical or thermal damage can lead to a loss of conductivity across a damaged pathway and performance degradation or failure of the circuit. We describe materials-based approaches to achieve autonomic healing of conductivity in both Li-ion battery electrode and microelectronic applications via microencapsulated healing agents. We discuss several different self-healing systems, damage and mechanical testing protocols, and potential applications with a focus on restoration of conductivity via delivery of liquid metal healing agent. Further, we discuss alternative methods to achieve conductivity restoration such as the solvent aided delivery of carbonaceous particles, and the *in situ* formation of conductive polymers. Through self-healing of conductivity in these damaged materials, battery and microelectronic device lifetime and reliability may be increased.

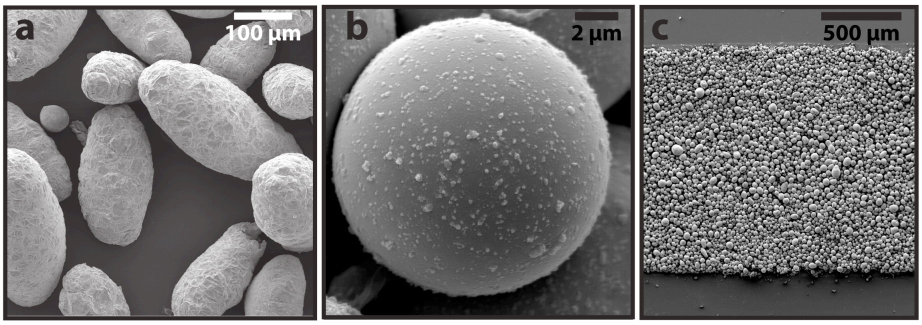

Figure 1: SEM images of (a,b) Ga-In liquid metal filled microcapsules and (c) Ga-In microcapsules patterned on a gold film.

We present a robust urea-formaldehyde (UF) technique for encapsulation and triggered delivery of conductive liquid metal, such as elemental gallium (Ga) or common Ga alloys (Ga-In, Ga-In-Sn), to the site of mechanical damage in a conductive material. These Ga-In filled capsules have been prepared at a variety of size scales ranging from 200 µm **(Fig 1a)** to ca. 10 µm **(Fig 1b)**, and have been directly patterned onto conductive films to minimize the amount of capsules required to achieve restoration **(Fig 1c)**.

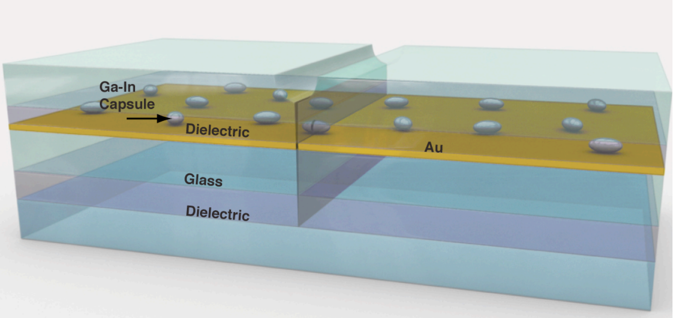

Figure 2: Schematic of the four-point bend specimen used to demonstrate restoration of conductivity using an encapsulated liquid metal as healing agent.

To demonstrate autonomic recovery of conductivity, a model multilayer circuit **(Fig 2)** is developed and tested in four point bending to provide controlled and repeatable damage to the conductive layer. Each specimen is continuously monitored via a normalized Wheatstone Bridge gage voltage, which ranges from 0 for a broken specimen (effectively infinite resistance) to 1 for an undamaged specimen. Through this methodology, we demonstrate for the first time, fully autonomic self-healing of conductivity, achieving up to 99% recovery of initial circuit performance after complete circuit failure and circuit recovery times of less than 500 µs **(Fig 3b).** Control specimens, with dielectric layers of neat epoxy, of epoxy with solid glass spheres, and of epoxy with solid Ga spheres, showed no self-healing effect **(Fig 3a)**.

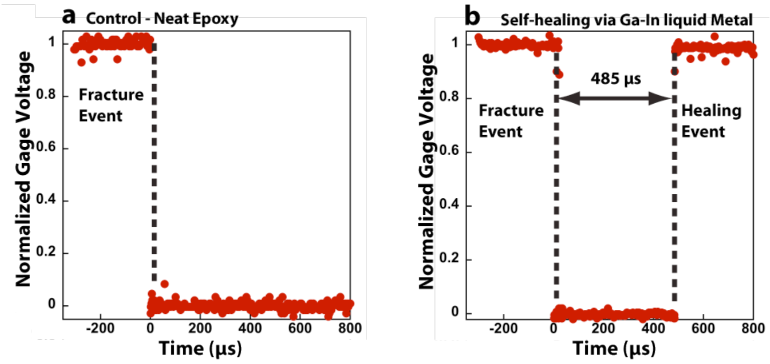

Figure 3: The normalized bridge voltage of (a) a neat epoxy control and (b) a self-healing specimen monitored via oscilloscope. No restoration is noted in the control case, and near full recovery is achieved in the self-healing specimen.