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Fast circuit breaker based on integration of Al/CuO nanothermites

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ABSTRACT

Pyroswitches and circuit breakers play an important safety role in electrical systems. A miniature one-shot circuit breaker based on the violent reaction of a nanothermite is presented for safety application as protection against overcurrent, external perturbation and short circuit of a broad range of equipment and systems. This device consists of two circuits assembled together to define a cavity. An ignition chip is placed into this cavity and ignites, within less than 100 μs, a few milligrams of nanothermites powder. The resulting violent reaction interrupts a thick copper connection within 1 ms. After the presentation of the device design, fabrication and assembly, we demonstrate the good operation and reproducibility of the device (100% of success rate) with a response time much lower than that of classical mechanical circuit breakers, which are slow. The response time can be tuned from 1.02 ms to 0.57 ms just by adjusting the mass of nanothermites from 5.59 to 13.24 mg, i.e., adjusting the volumetric solid loadings from 5.6 to 19%. The nanothermites-based circuit breaker presented in this paper offers unprecedented advantages: it is built using only safe substances and is based on a low-cost mass fabrication process that is compatible with electronics. The proposed concept is generic and can be applied to a large number of applications (electrical storage, aerospace manufacturing, human safety, demolition parachute opening, road vehicles, battery powered machines...).

1. Introduction

Energetic materials are the only attractive sources of “dormant” energy, exhibiting long shelf life (decades) that can very quickly deliver gas, heat, and chemical species. For context, the decomposition of thermites can produce ~4 MJ/kg, which approaches the combustion of hydrocarbon materials (~50 MJ/kg), whereas a modern chemical lithium-ion battery stores only 0.5 MJ/kg [1]. Therefore, energetic materials remain very attractive, even with a conversion efficiency of 10%, because they can provide fast reactions and high energy densities concomitantly with long shelf life, thus enabling autonomous actions under infrequent and extreme conditions better than any other systems. The technology for making traditional energetic materials still relies on either the physical mixing of solid oxidizers and fuels or the incorporation of oxidizing and fuel moieties into one single molecule, referred to as monomolecular energetic materials. Although much progress has been made in traditional energetic formulations and their integration into miniaturized devices, they still emanate *from old and unsafe technologies* based on the processing of granular solids. Manufacturing these granular substances into complex precise shapes is often difficult because of limitations in processing highly solid filled materials and the danger in processing energetic materials. In addition, there are as many different energetic materials as there are desired effects (rapid or slow energy release, high or low amount of gas generated), limiting their integration into generalized processes and hindering their incorporation into modern technologies and products. For two decades, nanotechnologies appear as the key to the development of future energetic materials. Nanothermites, obtained by mixing Al with oxide nanopowders (CuO, Fe_2O_3, Bi_2O_3, Sb_2O_3, MoO_3, I_2O_5, WO_3, ...) [2–7] have attracted much interest because they can release twice as much energy than the best molecular explosives in a much more controlled and safe manner. Nanothermites can also have better combustion efficiencies and better ignitability compared to typical explosives [8]. In addition, the high interfacial contact between the nanoparticles (NPs) and small diffusion length scales, among other possible mechanisms, enhance the chemical kinetics between Al and oxidizer, resulting in rapid pressurization and high energy release [5,9]. In this paper, we exploit the high-pressurization capability of Al/CuO nanothermites to design and fabricate a miniature nanothermites-based circuit breaker (CB) ideally suited to protect against overcurrent,

Abbreviations: CB, circuit breaker; PCB, printed circuit board; TGA, thermo-Gravimetric analysis; NPs, nanoparticles; Al-NPs, Al nanoparticles; CuO-NPs, CuO nanoparticles.

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external perturbation and short circuit of a broad range of equipment and systems. A circuit breaker is a switching device capable of making, carrying and breaking currents under normal circuit conditions. Further, a CB should be capable of interrupting the current at a succeeding current zero. All of these features make the CB an important component. Mechanical circuit breakers [10] take a relatively long time (over 1 ms) to open the circuit and have excessive volumes. A miniature (2.3 cm^3) nanothermites-based circuit breaker contains a switching unit, including a pyroMEMS, i.e. a pyrotechnical micro-chip capable of generating heat and pressure burst [9]. The use of pyroMEMS as a switching unit greatly miniaturizes the CB and ensures rapid interruption within less than 1 ms. After the presentation of the CB concept and design, the fabrication of each part of the device is presented in detail. The electrical testing achieved on several fabricated devices demonstrates 100% success of current interruption. Results also show that the current interruption time can be easily tuned from 1.02 ms to 0.57 ms just by adapting the nanothermites solids loading, i.e. the mass of nanothermites deposited on the pyroMEMS. The nanothermites-based CB presented in this paper offers unprecedented advantages, such as the following: (1) harmless manipulation of the substances for humans; (2) integrated fabrication framework enabling low cost as well as mass fabrication, reliability and nanoscale precision; (3) increased environmental protection, only safe and environmental friendly substances and components are chosen to produce the energetic layers; and (4) versatile design that can be applied to a large number of applications (electrical storage, aerospace manufacturing, human safety, demolition parachute opening, road vehicles, battery powered machines, . . .).

2. Materials and experimental methods

All PCBs (Printed Board Circuits) used in this paper are fabricated by CIRLY Company (France) using standard PCB technology. Al/CuO nanothermites prepared by mixing Al and CuO nanopowders are chosen because it possesses the following characteristics: a high energy release per unit of volume (3.9 kJ/g) and a high-pressure peak with the highest pressurization rate while being safe and relatively insensitive to ESD (electrostatic discharge) [11] in comparison with other gas generator nanothermites, such as Al/Bi_2O_3. Moreover, Al/CuO nanothermites feature higher combustion speed than the standard nanothermites couple (Al/MoO_3, Al/Bi_2O_3 and Al/WO_3) [12].

The CuO nanoparticles of random shapes are supplied by Sigma Aldrich with a characteristic dimension of 50 nm. The Al nanoparticles (Al-NPs) are supplied by US Research Nanomaterials, with a nominal diameter of 100 nm; they display spherical shapes with an alumina shell thickness of 4 nm, corresponding to a purity of 71%, calculated from TGA (Thermo Gravimetric Analysis) curves (see supplementary information file SI-1). Based on mass gain measurements (Δm), the mass of aluminum m_{Al} can be determined ($m_{Al} = \frac{2.M_{Al}}{3.M_O}.\Delta m$) with M_{Al} and M_O the molar mass of aluminum (27 g mol^{-1}) and oxygen (16 g mol^{-1}) respectively. Then the thickness of the oxide layer (t_{oxide}) is calculated according to Eq. 1.

$$t_{oxide} = R_0 \left(1 - \sqrt[3]{\frac{m_{Al_2O_3}}{m_{Al_2O_3} + \frac{\rho_{Al_2O_3}}{\rho_{Al}} m_{Al}}} \right) \quad (1)$$

where R_0 is the total particle radius; m_{Al} and $m_{Al_2O_3}$ are the masses of aluminum and alumina, respectively; and $\rho_{Al_2O_3}$ (3.97 g cm^{-3}) and ρ_{Al} (2.7 g cm^{-3}) are the densities of amorphous aluminum oxide and aluminum at room temperature, respectively. Al-NPs and CuO-NPs are then mixed in different ratios, including the fractional alumina content [5]. Nanopowders are weighed and mixed in hexane with ultrasound agitation to achieve good mixing. Fig. 1b displays a scanning electron microscopy image from Al/CuO mixing after ultrasonic mixing. These mixtures are then deposited into Nylon washers (2.7 or 3.2 mm in diameter and 1 mm in thickness, giving a volume of 5.7 ± 0.9 mm3 or 8.04 ± 0.4 mm^3) by drop casting. After the hexane evaporation, the nanopowder is pressed under an applied force of ∼ 2 daN. The pressure released by the nanothermites pellet is measured in a stainless steel cylindrical reactor, as described in a previous paper [5]. The free volume of the chamber is 53 ± 6 mm^3 and the Al/CuO mass inside is 8.3 ± 0.3 mg which corresponds to 3% volumetric solids loading.

The influence of the stoichiometric ratio of Al/CuO mixture on the pressure is investigated in this paper. Volumetric solids loading of Al/CuO is varied to study its effect on the CB's operating time as well.

3. Operation principle and CB design

The proposed CB is schematically illustrated in Fig. 2. The CB consists of two PCBs assembled to define a cavity of 39 mm^3 in volume (7 mm in diameter). The bottom PCB supports the pyroMEMS, i.e. the nanothermites ignitor on which an additional nanothermites pellet is glued. These two elements constitute the pyrotechnic actuator as detailed in Fig. 3. The top PCB has a separate copper track as part of the circuitry that must be disconnected as presented in Fig. 2(b).

For the demonstration, we make use of a 100-μm thick Cu track. The principle of operation is very simple and can be applied to a large number of applications just by adapting the nanothermites ignitor (see Fig. 2): under external command, in the form of a current ($I_{ignition}$) applied to the nanothermites ignitor, the fast and violent reaction of the Al/CuO nanothermites pellet safely integrated into a hermetic cavity made by the assembly of two circuits, cut and propel a thick Cu track, thereby interrupting the current flowing through it (I_{cc}).

The originality of our design relies on the simple soldering of the Cu track to be disconnected on the PCB's copper tracks. Therefore, the applied force necessary to eject it is independent of its thickness. For the demonstration, the overall size is set at 30 × 30 × 2.6 mm, and the copper track surface area is fixed at 8 × 10 mm. The copper track is brazed on the PCB's Cu layer (brazing surface is of 8 mm^2) using $Sn_{42}Bi_{57\cdot6}Ag_{0.4}$ paste. The force required to disconnect the copper track has been experimentally measured at 41 ± 7 N. Considering the copper track surface area of 80 mm^2, a pressure greater than 1.1 MPa must be produced in the cavity.

As illustrated in Fig. 3, the pyrotechnic actuator contains one nanothermites ignitor as presented in [13], which includes a Pyrex chip with a thin film resistance on which fifteen Al/CuO bilayers are sputtered, with each layer being 200 nm in thickness. A pellet of Al/CuO nanothermites is prepared as described in the methods section. When the current is supplied to the ignition chip, the chemical reaction occurs within less than 1 ms ($I_{ignition}$), and sparks are spread to the nanothermites pellet, which reacts violently, producing the pressure burst plotted in Fig. 5. The ignition time, i.e. the delay between the application of $I_{ignition}$ (ignition current) and the appearance of sparks, as a function of the current applied to the nanothermites ignitor is presented in the Fig. 4. The minimum ignition time, 0.36 ± 0.07 ms, is obtained for an ignition current of 2 A. The fire/no fire threshold is 0.5 A, which means that there is no ignition before this 0.5 A.

The nanothermites ignitor contains only 282 μg of Al/CuO that can generate a maximum pressure of 0.14 MPa [5], not sufficient to eject the copper track (1.1 MPa of pressure is required). Therefore an additional mass of Al/CuO nanoparticles mixture is glued on the nanothermites ignitor. When preparing the nanothermites pellet, two parameters are important to control the pressure burst: