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Magnetoelectric macro fiber composite

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ABSTRACT

This paper describes the fabrication and performance results of a magnetoelectric macro fiber composite (ME MFC). The magnetoelectric composite was fabricated by bonding a magnetostrictive layer to a piezoelectric layer using a novel approach of low temperature transient liquid phase (LTTLP) bonding. The composite was diced into 150 micron wide fibers and bonded to a custom designed copper flexible circuit using a spin coated low viscosity room temperature curing epoxy. ME MFC's with varying ferrite thicknesses of 0.6 mm and 0.5 mm were fabricated and characterized for energy harvesting. The composite with 0.6 mm ferrite thickness achieved an open circuit voltage of 101 mV (ME voltage coefficient of 6740 mV/cmOe) and peak power of 3.1 nW across 356 kΩ matching load at 264 Hz.

1. Introduction

Macro fiber composites (MFC) were invented by NASA in 1996 as a surface conformable and flexible piezoelectric ceramic device for controlling structural vibration, noise, and deflections [1]. By being thin, sealed in polyimide and capable of being formed in any geometric shape, such MFC's are versatile enough to be employed as actuators with large deformation and sensors for structural health monitoring and energy harvesting [2]. Therefore, this MFC methodology was chosen to create a flexible magnetoelectric device capable of low frequency AC magnetic field and vibration harvesting. Push–pull type ME composite laminates have previously been found to be extremely sensitive magnetic sensors with low noise [3]. In such sensors, the magnetostrictive layers are bonded externally to laminated piezoelectric fibers. Our macro fiber composites employed magnetoelectric composite fibers in which the magnetostrictive layer was directly bonded internally to the piezoelectric layer.

Magnetoelectric (ME) composites have been found promising for sensors, phase shifters, filters, and tunable transformers. Such devices usually consist of a composite structure that includes a magnetostrictive phase in contact with a piezoelectric phase. The efficiency of the elastic coupling between the two phases depends upon the strain transfer occurring at the interface. Magnetoelectric response of a ME composite is measured as ME voltage coefficient αME and the relationship between the magnetic field induced strain in the magnetostrictive material and the generated electric field in the piezoelectric material is given by [4]:

$$\alpha_{ME} = \left|\frac{\partial T}{\partial S} \times \frac{\partial D}{\partial T} \times \frac{\partial E}{\partial D}\right| \times \frac{\partial S}{\partial H} \quad (1)$$

where S is the mechanical strain, T is the mechanical stress, D is the electric displacement, E is the electric field, and H is the magnetic field.

The magnetoelectric response can be maximized by improving the interfacial properties in terms of matching the mechanical impedance between the magnetostrictive and piezoelectric layers [5,6]. Epoxy bonding has been found to perform better than both a Ag–Si alloy with 600 °C working temperature and a thin borosilicate with 500–600 °C bonding layers [7]. ME laminate composites are mostly fabricated by bonding a magnetostrictive material to a piezoelectric macro fiber composite [8] or a piezoelectric laminate composite [9]. The mechanical coupling is poor due to the polymer laminate between the piezoelectric MFC and the magnetostrictive layer. In ME thin film composites, the addition of a Pt layer between the piezoelectric film and the magnetostrictive film

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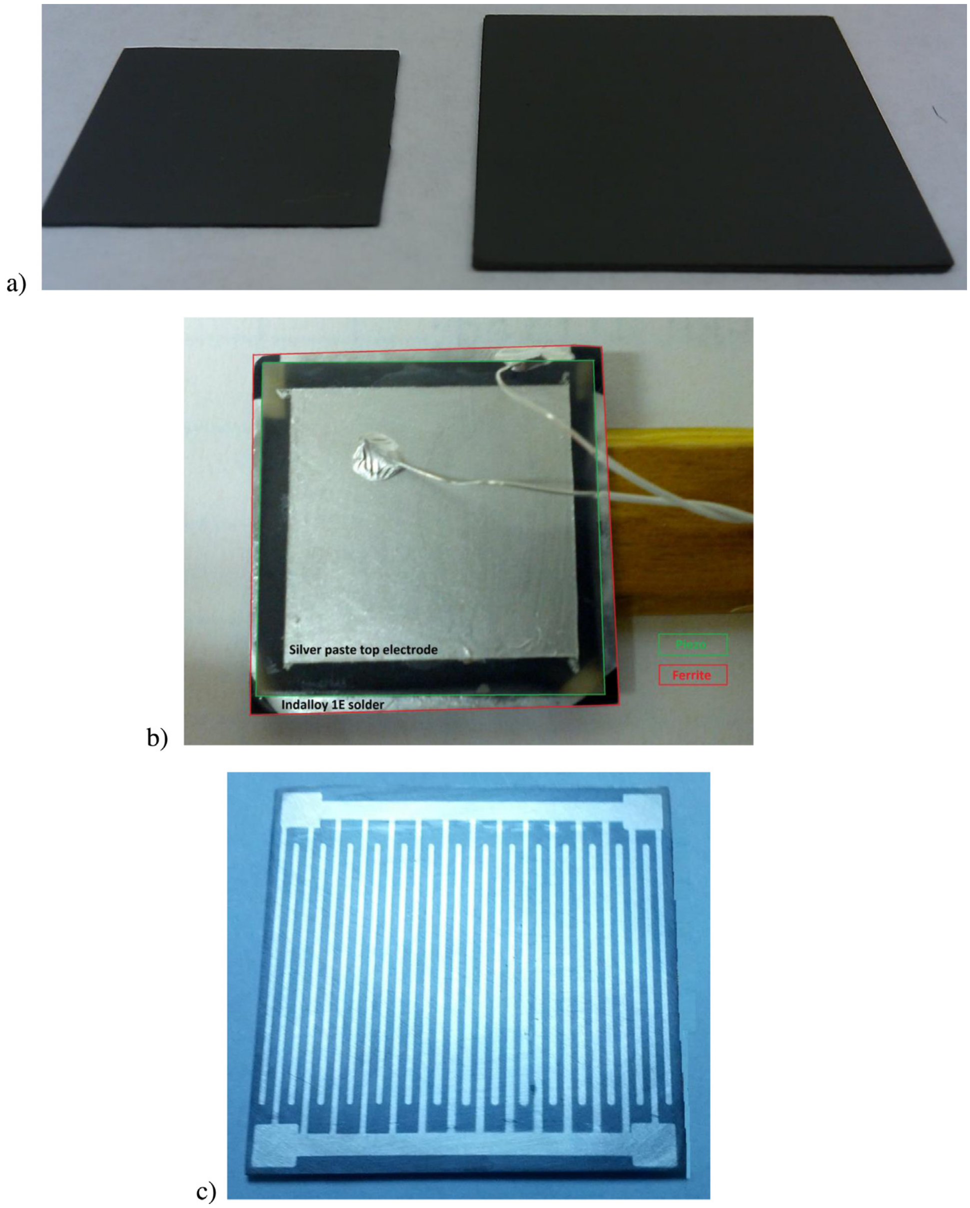

Fig. 1. (a) Ferrite 40.011 fired sheet and ME soldered composite with (b) d_{31} mode electroding using silver paste conductors and c) d_{33} mode electroding using Pt conductors.

has been shown to double the magnitude of ME coefficient [10]. In the case of bulk ME composites, the addition of an embedded metallic layer has also resulted in improved ME performance by suppressing interdiffusion between the cofired piezoelectric and magnetostrictive layers [11]. These co-fired ME composites limit the choice of the magnetostrictive, conductive and piezoelectric materials to that which can withstand >800 °C processing [11,12]. Transient liquid phase (TLP) bonding has been in use for centuries but has recently come to prominence in aerospace and semiconductor industries for the joining of two metallic surfaces [13]. The process entails a thin interlayer metal containing a melting point depressant that melts and fills the voids of the two metal surfaces in contact. This depressant metal diffuses into the parent metal, undergoes isothermal solidification and then upon cooling, the joint becomes homogeneous. Another variant of TLP bonding that employs a low temperature melting solder is low temperature transient liquid phase bonding (LTTLP) [14]. In this latter case, ceramic or metal surfaces are bonded by utilizing a base metal coating on each of the mating surfaces and then adding a low melting solder between the base metal layers on each bonding surface. At the solder melting point, some of the base metal dissolves in the solder and undergoes isothermal solidification. The resultant solder-base metal alloy has a higher eutectic point than the solder melting point and therefore, the resultant bond can withstand higher temperatures than the temperature at which bonding occurred.

Building upon these prior findings, we demonstrate here a metallic bonding process for attaching the piezoelectric and magnetostrictive layer in ME laminate composites. The constraints on the bonding process included the thin dimensions of the interface and process temperature below the Curie temperature of the magnetostrictive and piezoelectric layers. Using this low temperature metallic bonding technique, the ME composite was fabricated and then singulated into fibers. These fibers were then bonded to a flexible electrical circuit to realize the first magnetoelectric macro fiber composite (to our knowledge at time of publication).

2. Experimental procedures

The ceramic raw materials were acquired from Piezo Systems (5A4E 0.127 mm sheet) and Electroscience (Type 40.011 ferrite