Sensors and Actuators A 226 (2015) 107–115

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Micromachined rectangular-spiral-coil actuator for radio-controlled cantilever-like actuation

Jeffrey Fong, Zhiming Xiao, Kenichi Takahata *

Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, BC V6T1Z4, Canada

A R T I C L E I N F O

Article history:
Received 10 October 2014
Received in revised form 30 January 2015
Accepted 16 February 2015
Available online 24 February 2015

Keywords:
Microactuator
Shape memory alloy
Cantilever
Spiral coil
Wireless control
Resonant induction heating

A B S T R A C T

This paper reports of a micromachined shape-memory-alloy (SMA) actuator in the shape of a rectangular spiral coil that is designed to perform cantilever-like actuation. The SMA-coil actuator itself forms a passive resonant circuit that functions as a wireless heat source activated using external radio-frequency (RF) electromagnetic fields for frequency-selective control of the actuation. The SiO_2 stress layers are selectively patterned on the actuator structure of nickel–titanium SMA, or Nitinol, to manipulate the cantilever profile at the nominal cold state. RF radiation with varying field frequencies shows strong frequency dependence of wireless heating, actuation displacement, and force generation by microfabricated actuators with resonant frequencies of 170–245 MHz. The actuators excited at resonance exhibit maximum out-of-plane displacement and force of 215 μm and 71 mN, respectively. The developed wireless SMA actuator not only provides >2× the force and 2× more power-efficient response compared to the preceding design with similar self-heating mechanism but also offers broader potential applications brought by its commonly adopted cantilever-based actuation.

1. Introduction

Microactuators have been enabled with a variety of actuation mechanisms including electrostatic [1], piezoelectric [2], electromagnetic [3], electrothermal [4], and shape memory alloy (SMA) [5]. As every mechanism has its advantages and disadvantages [6,7], choosing the appropriate mechanism depends on the intended application. In general, electrostatic actuators have low power consumption and fast response times, but require high voltages and only produce small displacements. Piezoelectric actuators generate large forces and have fast response times but also require high voltages for small displacements. Electromagnetic actuators generate large forces but do not benefit from miniaturization and often require non-standard techniques for micromachining of magnetic materials. Electrothermal actuators also generate large forces but consume a large amount of power to produce relatively small displacements. Implementing these mechanisms usually requires connecting the microdevices to an external power source via electrical wires; but this is not feasible for many applications such as wireless sensor/actuator networks, microrobotics, and medical implants. Batteries could be included for such applications; however, they have a limited lifetime and would increase the overall device size, limiting their application range, especially in the medical areas. Passive, wireless actuation does not require an internal power supply or active circuitry for actuation control and may be more useful for the aforementioned applications. Wirelessly powered actuators have been reported with a few different mechanisms including electrostatic actuation via surface acoustic waves [8] and magnetic fields [9], magnetic actuation [10,11], and heating via energy beams for bimetallic [12] and SMA actuations [13].

SMA actuators offer attractive features of large forces and high work output per unit volume without the need for high voltages. Nitinol is an SMA used in many applications because it is also biocompatible, ductile, and resistant to corrosion [14–17]. Although SMA actuation is relatively slow as it relies on metallurgical phase transition, this drawback is not a major concern in many cases, leading to studies for a broad range of applications including biomedical devices [18–22] and robotics [23–25]. Micromachined, wireless SMA actuators with energy transfer by radio-frequency (RF) electromagnetic fields have been reported [26,27]. These devices consisted of frequency-dependent wireless heating coils bonded to Nitinol actuators. Joule heating occurred in the coils when exposed to an RF field whose frequency was tuned to the resonant frequency of the coil; the heat transferred to the movable Nitinol microstructures and caused their actuation. This type of device allows for control over individual actuators across multiple ones by assigning different resonant frequencies to the corresponding coils and by modulating the frequency of the

* Corresponding author. Tel.: +1 604 827 4241; fax: +1 604 822 5949.
E-mail address: takahata@ece.ubc.ca (K. Takahata).

http://dx.doi.org/10.1016/j.sna.2015.02.024
0924-4247/

applied RF field [27]. This method is advantageous over energy-beam assisted heating because it does not require complicated optics or an unobstructed path for the beam to reach the actuator; for in vivo applications, RF fields can penetrate tissue and activate medical devices inside the body. However, large thermal gradients between the heaters and the actuators in these devices caused delayed activation. To overcome this problem, Nitinol was micromachined into a planar spiral-coil inductor that received RF power wirelessly to directly generate heat by itself and actuate, removing the need for a separate receiver coil [28]. Although the temporal response was improved with this actuator design, the maximum force available was relatively small (30 mN as compared to, e.g., 840 mN from a similarly sized, typical cantilever actuator based on Nitinol [27]). Another weakness of this design is that the mechanical coupling between the actuator and the element being moved on the substrate is not straightforward as the coupling location is the coil's center that is enclosed by the actuator's ring-shaped anchor.

This paper reports a wirelessly powered, micromachined Nitinol actuator designed to offer cantilever-like motion with increased maximum force not available with the previously reported device [28]. The micromachined coil structure allows for wireless heating directly in the Nitinol via resonant RF fields. By patterning Nitinol into a rectangular-shaped spiral coil, the longitudinal coil lines act as a cantilever structure that produces out-of-plane displacements during heating. Cantilevers are one of the most common MEMS actuators; therefore, this new design could significantly expand the applicability of wireless MEMS actuators in biomedical, robotics, and other fields. The working principle, design, fabrication, and testing of the developed actuator are provided in the following sections.

2. Working principle and actuator design

The cantilever-like spiral-coil SMA actuator is created by patterning a layer that provides stress onto a rectangular-shaped Nitinol coil, causing bimorph deformations in the coil (Fig. 1). By adjusting the length and thickness of the stress layer deposited on the Nitinol structure, the displacement of its free end can be altered. The coil structure acts as an inductor, or a receiver antenna, to which RF power is inductively transferred; by incorporating a fixed capacitor into the design, an inductor–capacitor (*LC*) circuit is formed with a characteristic resonant frequency, f_R. When the device is exposed to an RF electromagnetic field with a frequency matching the f_R value of the actuator, it most efficiently generates an ac electromotive force (EMF). The ac current resulting from the EMF produces Joule heating directly in the coil. When its temperature passes the activation (austenite-phase) temperature, T_a, defined in the particular Nitinol, the coil returns to its remembered flat shape. If the RF field is modulated to a frequency outside of the actuator's active range (Fig. 1) or simply turned off, the actuator cools down below T_a and the Nitinol returns back to the martensite phase where the SMA becomes compliant. The stress layer deforms the SMA structure once again so that actuation can be repeated.

In the actuator design, SiO_2 is used as the stress layer to exploit two mechanisms that work together: (1) plasma-enhanced chemical vapor deposition (PECVD) of SiO_2 results in intrinsic compressive stress which depends on the processing conditions [29]; (2) SiO_2 has a smaller coefficient of thermal expansion ($0.5 \times 10^{-6}/^{\circ}C$ [30]) than that of Nitinol ($6.6–11 \times 10^{-6}/^{\circ}C$ depending on the phase [31]). These two mechanisms combine so that PECVD SiO_2 deposited at elevated temperatures leads to compressive stress after cooling it down, bending the bilayer away from

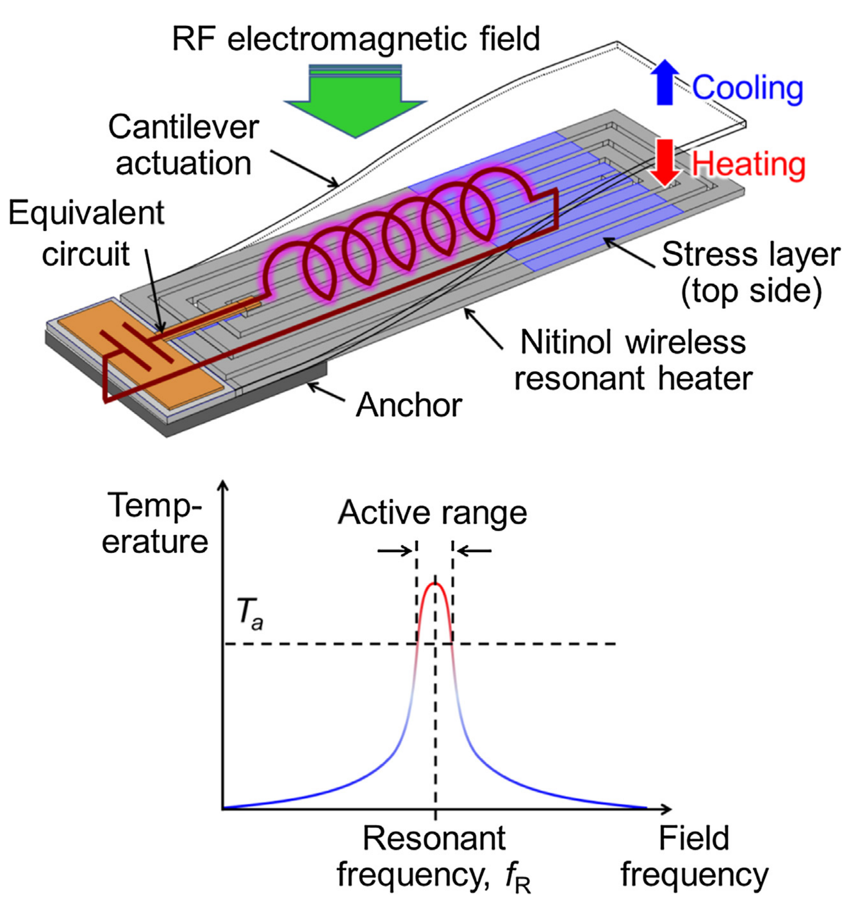

Fig. 1. Conceptual diagram and working principle of the wireless, cantilever-like actuator based on a resonant Nitinol coil with an integrated capacitor.