Sensors and Actuators A 219 (2014) 65–72

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

MEMS-based ultrasonic transducer as the receiver for wireless power supply of the implantable microdevices

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ARTICLE INFO

Article history:
Received 19 May 2014
Received in revised form 10 July 2014
Accepted 10 July 2014
Available online 26 August 2014

Keywords:
Wireless power supply
Ultrasonic transducer
MEMS
Implantable micro devices
Thick piezoelectric film

ABSTRACT

This paper investigates a wireless power supply for implantable devices with a MEMS-based ultrasonic transducer. The transducer employs a piezoelectric thick film prepared by bonding and thinning technologies. A continuous ultrasound wave of 40.43 kHz is transmitted in two media: water and biological tissue. This transmitted power is received by a MEMS transducer, demonstrating a peak power transfer of 35 μW under the sound energy density of 3.7×10^{-9} J/cm^3 at a reception distance of 20 mm in a water tank, and a peak power of 49 μW under the sound energy density of 1.25×10^{-8} J/cm^3 at a reception distance of 22 mm in a pig hind leg tissue. The pressure sensitivity of this device is about 0.296 mV/Pa in the frequency of 40.43 kHz. In a progressive field, the energy density of 3.7×10^{-9} J/cm^3 and 1.25×10^{-8} J/cm^3 would be achieved at the intensity of 589.3 μW/cm^2 and 1.2 mW/cm^2, which are both below the FDA safety limit. The output power of the device under situations of misalignment at various reception angles is also discussed in detail based on experimental results.

1. Introduction

With the increasing interests in biomedical monitoring and sensor network applications, the power supply of the implanted bio-chips and smart devices is becoming an important urgent issue [1,2]. The conventional energy supply method by battery has some significant drawbacks: large size, toxic leakage and integrated difficulty, which lead to the application limitation for the implantable smart MEMS devices (ISMD) [3–5]. In order to resolve this issue, wireless energy transmission technology has been proposed and developed rapidly. Wireless energy transmission technology includes two major mechanisms, electromagnetic method and ultrasonic method. The first one has high transmission efficiency in the epidermal tissue. However, the transmission efficiency will be reduced for the RF absorption caused by tissue, and the transmission process is easily disturbed by external electromagnetic fields [6–8].

Ultrasonic waves have been widely used in human organs for perspective testing and observation of fetal development in pregnant women. Compared with electromagnetic method, ultrasound technology is more suitable for ISMD due to its long transmission distance in tissue and electromagnetic immunity [9].

Ultrasonic transducers can be divided into two types, capacitance mode and piezoelectric mode, as their working mechanism. In capacitance mode, the output property of the capacitance transducer is affected by the distance variation between the capacitor plates by ultrasonic vibration. Recently, some capacitive ultrasonic transducers have been used as a MEMS-based electrostatic ultrasonic transducer [10–12]. The capacitive ultrasonic transducers (CUT) are limited for the capacitors need to be re-polarized for a period of time.

Piezoelectric ultrasonic transducer (PUT) utilizes piezoelectric materials to convert the acoustic energy into voltage outputs. Since the reliable piezoelectric materials have a mature preparation, it attracts lots of concerns of researchers. The earlier reported implantable PUT directly uses piezoelectric ceramics as an ultrasonic receiver, wherein the receiver is a disk-shaped piezoelectric ceramic block with a pasted metal horn (15 mm diameter ball with the package) in order to improve the surface compressive stress [13]. The maximum power output of −40 dB in the distance of 25 mm in fat tissue was realized. The other ultrasonic wireless transmission system using circular piezoelectric ceramic block as the receiver (diameter of 20 mm and thickness of 2 mm) has been reported [14]. This work resulted in an energy transfer at a distance of 30 mm with the stringent requirements of the transmission

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http://dx.doi.org/10.1016/j.sna.2014.07.008
0924-4247/

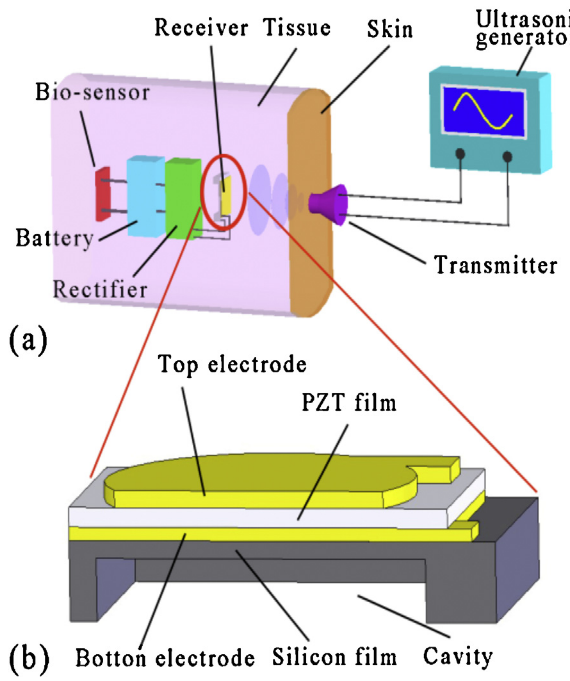

Fig. 1. (a) Schematic of ultrasonic wireless power supply in vivo and (b) profile of the receiver.

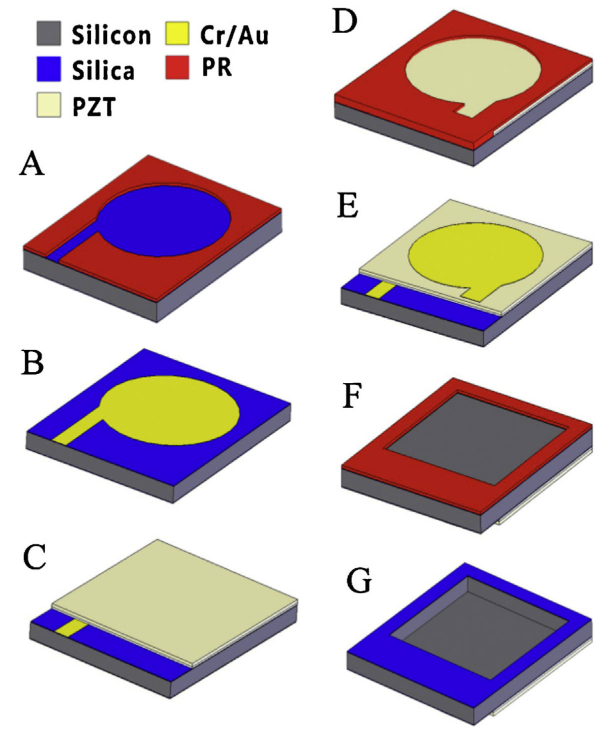

Fig. 2. Fabrication process of the receiver. (a) Patterned photoresist on silicon oxide surface; (b) sputtering Cr/Au bottom electrode; (c) piezoelectric ceramic bonding and thinning; (d) patterned photoresist on PZT film; (e) sputtering Cr/Au top electrode; (f) patterned photoresist on back side of the silicon substrate; (g) etching of the silicon.

direction. However, the major drawback of this PUT prepared by piezoelectric is the excessive size, which limits its development in implantable application.

The MEMS technology solves the size problem of the PUT by sputtering piezoelectric films. A MEMS-based 3D array PUT was prepared by sputtering niobium-doped lead zirconate titanate (PNZT) on a pre-prepared curved substrate to increase the transmission range of ultrasonic wave [15]. The cell size is 100 μm in diameter and the resonant frequent band of is 4.5–5.6 MHz. The peak sensitivity of this device is 85 kPa/V, but the actual energy transmission capacity was not discussed in this work. The other PUT of d_{33} type prepared by a sputtering process was reported in gathering the surface strain of the film with the interdigitated electrodes [16]. The cell size is 1 mm × 1 mm with the PZT film thickness of 1 μm, the resonant frequency is 44 kHz and the device is excited by an ultrasonic speaker in the air. A PUT with 6 μm-thick PZT film by repeatedly sputtering method on silicon film was reported as ultrasonic transmitter [17]. The sound pressure level of 117 dB in 300 mm was obtained at the resonant frequency of 92.6 kHz in the air, but the application as an ultrasonic receiver has not been discussed in this work. The piezoelectric coefficient of the sputtered PZT film is far below one of the bulk piezoelectric materials due to the poor crystalline of the sputtered PZT film. For the above reasons, an ultrasonic transducer with high piezoelectric properties and tiny volume will be valuable for development of the implantable PUT.

In this work, the MEMS-based ultrasonic transducer with piezoelectric thick film is proposed for wireless power supply. The performance of the ultrasonic transducer in water and tissue is analyzed based on the experimentally results. The results show that this transducer can realize the ultrasonic wireless energy transmission both in water and tissue for the power supply for implantable devices.

2. Design and fabrication

The schematic of the ultrasonic wireless power supply system is shown in Fig. 1(a). The ultrasonic transmitter emits ultrasound into the human body with ultrasound coupling gel, and the ultrasonic transducer as the receiver in tissue absorbs the ultrasonic wave in the resonant way and converts the acoustic energy into electrical energy, which is stored in super-capacitors or powers a biosensor directly after rectification by diodes. The structural profile of the receiver is shown in Fig. 1(b), a PZT film with the thickness of 40 μm is prepared through bonding and mechanically thinning methods, which have been reported in our previous work [18] and the natural frequency is adjusted by changing the thickness and side length of the silicon film and cavity, respectively.

The long-wave has a longer transmission distance in water similar to the sonar principle [10,19]. The frequencies from 20 kHz to 30 kHz are very close to the human distinguished range, so that there may be an unbearable noise at this range in the coupling process of the transmitter to skin. Meanwhile, there are many ultrasonic cleaning equipments working at the resonant frequency of 40 kHz. Therefore, 40 kHz is selected as the designed frequency of the ultrasonic receiver. We designed an implantable ultrasonic receiver with bonding piezoelectric film, which can absorb ultrasound.

The resonant frequency of this receiver is simulated by finite-element software of ANSYS. The calculated results show that the natural resonant frequency is 39.918 kHz of the resonant film in the parameters of 3.2 mm × 3.2 mm in side length and 40 μm in thickness in the air.

Fig. 2 shows the fabrication process of the receiver. Firstly, the bottom Cr/Au layer electrode was sputtered on a silicon substrate and patterned by the lift-off process (Fig. 2(a) and (b)). Secondly, the diced piezoelectric ceramic block (thickness of 400 μm, C-6, Fuji Ceramics, Inc.) was pasted on the bottom electrode with conductive resin (DAD-91H, Shanghai Institute of Synthetic Resins) by screen printing. The bonding conditions include a constant pressure of 1120 Pa, heating temperatures of 135 °C for 2 h and 175 °C for 2 h in vacuum environment. A piezoelectric film with thickness of 40 μm was obtained by mechanical grinding and polishing