Sensors and Actuators A 243 (2016) 1–6

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Electrochemical actuator with a short response time: A new actuation regime

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ARTICLE INFO

Article history:
Received 21 December 2015
Received in revised form 26 February 2016
Accepted 1 March 2016
Available online 10 March 2016

Keywords:
Actuators
Electrolysis
Bubbles
Microsystems

ABSTRACT

The lack of fast and strong microactuators is a well-recognized problem in the MEMS community. Electrochemical actuators can develop high pressure but they are notoriously slow. Water electrolysis produced by short voltage pulses of alternating polarity can overcome the problem of slow gas termination due to spontaneous ignition of the reaction between hydrogen and oxygen in nanobubbles. An actuation regime with the termination time as short as 100 μs was demonstrated previously. Here we describe a new actuation regime, for which the gas pressure is relaxed just in 10 μs and a minimal degradation of the electrodes is observed. The actuator consists of a microchamber filled with an electrolyte and covered with a flexible silicon nitride membrane. The membrane bends outward when the pressure in the chamber increases. The new regime is characterized by the appearance of short-lived microbubbles in between the electrodes. Fast termination of gas and high pressure developed in the chamber are related to a high density of nanobubbles in the chamber. The physical processes happening in the chamber are discussed as well as problems that have to be resolved for practical applications of this actuation regime. The actuator can be used as a driving engine for microfluidics.

1. Introduction

The last decennium has witnessed an impressive trend to miniaturize systems of virtually any kind. This trend has many reasons: small systems are often cheaper to produce, they can have properties large systems have not, and they may facilitate use of large systems (cars, for example). An important and generic component in microsystems is the actuator. It plays the role of a motor transforming electricity or other kind of energy into mechanical motion. In contrast with large scale systems, where effective engines are available (internal combustion or electromagnetic motors), microsystems suffer from the lack of strong and fast actuators [1,2]. Small electromagnetic motors cannot generate forces of useful magnitude due to unfavorably scaling of coils, and internal combustion engines [3] perform poorly due to increased heat losses via the volume boundary [4,5] when the volume decreases.

Existing microactuators are using mostly two types of forces [1,2,6,7]: electrostatic forces, which are weak, and those generated by thermal expansion, which are slow. Fast and strong piezoelectric elements are difficult to combine with microtechnology, they need a high voltage for actuation, and have a small stroke. Electroactive polymers are promising in the field of robotics [8–11] but they are not well suited for a number of applications in microsystems. Actuators based on the electrochemical decomposition of water were also discussed in many papers [12–19] but they are notoriously slow. One can produce a large amount of gas in a short time but it is impossible to get rid of this gas fast as well.

Electrochemical decomposition of water is a well-known process but electrolysis performed in microsystems on a short-time scale brought unexpected surprises [20] (as a recent review see [21]). It was found that the local current density can be three orders of magnitude larger than that for the normal long-time (>1 ms) electrolysis. The local concentration of gas in the short-time regime (1–100 μs) was more than 1000 times larger than the saturated concentration of gas at normal conditions (the relative supersaturation $S > 1000$). Under these conditions nucleation of bubbles must happen homogeneously, which was indeed observed [22]. Applying potential with fast changes of polarity (>20 kHz) visible production of gas disappeared but the current via the electrolyte practically did not change. A number of effects indicated that the gas disappearance is related to the reaction between hydrogen and oxygen

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http://dx.doi.org/10.1016/j.sna.2016.03.002
0924-4247/

that happens spontaneously in nanobubbles with sizes smaller than 200 nm.

The phenomenon of gas combustion in nanobubbles is puzzling (see, for example, [23]). It is not clear why the reaction is ignited. High Laplace pressure in the bubbles at room temperature is not sufficient to ignite the reaction. Fast microseconds dynamics can be important but, taken alone, can hardly explain the ignition of the reaction. For the ignition one has to overcome a high energy barrier, which seemed not possible at room temperature. Moreover, in contrast with the standard combustion theory [24] the reaction happens without significant temperature increase in the bubbles [20] although large energy produced in the process manifests itself in a number of measurable effects. Combustion reactions inside of small volumes is an additional mystery of nanobubbles. The other well-known problem is the observed unexpectedly long stability of surface [25] and bulk [26] nanobubbles filled in with the gases, which are not able to react.

In spite of poor understanding of the reaction mechanism the discovered phenomenon can be used to build a fast and strong actuator [27]. This actuator consists of a microchamber covered with a flexible membrane and is filled with an electrolyte. The electrolysis is obtained by short voltage pulses of alternating polarity. The pressure in the chamber increases and bulges the membrane, but no visible bubbles are formed. This is because most of the gas is packed in nanobubbles, which do not scatter light. When the pulses are switched off, pressure relaxation takes place in less than 100 μs or so. The actuator cannot be compared to the electrochemical actuators using water electrolysis, for which the relaxation time scale is minutes [19].

In this paper we describe a new actuation regime, for which a high pressure can be reached while pressure relaxation takes place in less than 10 μs. Moreover, in contrast with the regime described in [27] the degradation of electrodes is much reduced.

2. Experimental

We did experiments with devices (see Fig. 1) fabricated on Si wafers covered with a layer of silicon nitride (530 nm thick). Platinum electrodes were deposited on top of this layer. Underneath of the electrodes there is a heat sensor made of polysilicon. Within the chamber area the nitride was released by etching the Si wafer from the back side so that the nitride layer played the role of a membrane. The chamber and filling channels were isotropically etched in borofloat glass. The silicon and glass wafers were anodically bonded. Nominal dimensions of the chamber are 100 μm × 100 μm × 5 μm. The details of the design and fabrication were reported earlier [27]. The chamber was filled via the channel with 1 M solution of Na_2SO_4 in deionized water. The in/outlet openings of the channel were sealed after the filling.

Square voltage pulses of alternating polarity were applied to the electrodes at frequencies $f \sim 100$ kHz. To get high currents we use the electrochemical cell in the ohmic regime applying voltage amplitudes above 5 V [27]. Gas formation in the chamber was observed with a homemade stroboscope [28] (10 μs flashlight and a wavelength of $\lambda \approx 530$ nm).

Gas production in the chamber resulted in a pressure rise and a deflection of the membrane. Detailed information on the pressure was collected by observing deflection of the membrane nearby its center with a vibrometer (Polytec MSA-400). The laser beam ($\lambda = 633$ nm, spot size 1.5 μm) was focused on an opaque spot on the back side of the membrane to prevent possible scattering by occasional microbubbles formed in the chamber. The current and movement of the membrane were recorded in separate channels of the instrument. The membrane deflection d was calibrated by applying a static gas pressure, giving $\Delta P = 2.03d + 0.27d^3$ [27], where ΔP is the overpressure in bars and d is in μm. Note that the resonance frequency of the membrane is estimated as high as 0.7 MHz so that this expression can be applied for the frequencies used in our experiments.

3. Results

Normal actuation of the device was described in ref. [27]. It was demonstrated that the pressure in the chamber can be as high as $P = 4.6$ bar and the time for pressure relaxation can be as short as 100 μs. The actuator works well at frequencies $f > 20$ kHz. At high frequencies very little gas is visible in the chamber as one can see in Fig. 2(a) and (b), which correspond to $f = 150$ and 200 kHz, respectively. Both images were made at the time moment $t = 400$ μs and the process ran at a voltage amplitude $U = 8$ V. At lower frequencies the amount of visible gas increases and below 20 kHz the chamber becomes completely filled with gas and actuation becomes impossible. A small amount of visible gas in the chamber exists in the form of microbubbles located above the electrodes. The new actuation regime manifests itself when the process is run longer. In this case a faint contrast appears in between the electrodes. For example at $t = 600$ μs it can be seen in Fig. 2(c) and (d), which also correspond to $f = 150$ and 200 kHz, respectively. This contrast resembles rather large microbubbles (10–20 μm in diameter), which appear out of focus due to motion blur. These bubbles appear in the chamber just for a few microseconds and are accompanied by significant pressure jumps in the chamber (see below, Fig. 3(b)).

A typical response of the membrane on the electrical pulses with amplitude $U = 9$ V at frequency $f = 100$ kHz is shown in Fig. 3(a). Well visible oscillations are superimposed on the monotonously increasing membrane deflection. These oscillations are in phase with the driving pulses. As was explained in [27] they are related to the reaction happening in nanobubbles containing a stoichiometric mixture of H_2 and O_2 gases. The pressure responds to both positive and negative halves of the pulses but the response is asymmetric in general. The monotonous deflection of the membrane is due to unburned gas. For example, if a bubble contains only hydrogen or only oxygen the reaction does not happen and such a bubble will contribute to the pressure increase in the chamber. This gas is also collected in

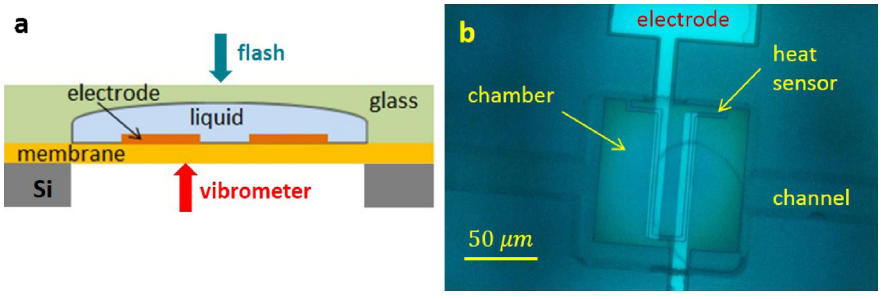

Fig. 1. (a) Schematic representation of the chamber. (b) Top view of the actuator. The chamber, filling channels, and electrodes are visible.