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Design and Fabrication of a Nonlinear Micro Impact Oscillator

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Abstract

In this paper we describe the design and fabrication of a mechanical autonomous impact oscillator with a MEMS resonator as the frequency control element. The design has been developed with scalability to large 2-D arrays of coupled oscillators in mind. The dynamic behaviour of the impact oscillator was numerically studied and it was found that the geometry nonlinearity has an effect on the static pull-in voltage and equilibrium position. The external driving power can alter the frequency of the impact oscillator. The autonomous nature of the oscillator simplifies the complexity of the drive circuitry and is essential for large 2-D arrays.

Keywords: Nonlinear; Electrostatic; Impact oscillator; Autonomous

1. Introduction

Collective modes of oscillation in arrays of non-linear micromechanical oscillators have been observed. Coupled systems are thus now receiving increased attention, as these complex behaviours due to the interactions between the different coupled elements becomes better understood [1, 2]. This complexity of the non-linear and collective behaviours in MEMS systems can potentially be exploited to create novel sensor systems. Using the normally detrimental fact, that micromechanical oscillators on the same substrate suffer from unintentional crosstalk and frequency locking, as a benefit rather than a problem will lead to new design principles that could revolutionise the design of MEMS systems. However a restriction on the development of arrayed micromechanical oscillator systems is the requirement of; i) providing the drive and readout circuitry across the 2-D array; and ii) providing an active circuit in each sensor pixel, limiting the size and complexity possible for an array. With the high Q array modes found in non-linearly coupled systems and the ability to functionalise different parts of the micromechanical array, offering the possibility of improved sensitivity and species discrimination over single sensors [3], then it is imperative to overcome these restrictions. To this end, we have designed an autonomous micro impact oscillator that self drives overcoming the issues with drive circuitry that is one of the main limits to array size. Here we present a preliminary study of this electrostatic micromechanical impact oscillator.

2. Design and simulation

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2.1. Principle of Operation

The core of the impact oscillator as schematically shown in Fig.1a is a moveable capacitive plate in a thin Si_3N_4 membrane on a back etched silicon handle chip. The counter electrode is formed on a separate substrate that the membrane chip is hybridised to. The design is such that it can be scaled to 2-D using the same fabrication techniques. The system works by charging up the metallised Si_3N_4 plate and when it has been pulled down due to the electrostatic force, it discharges on the counter electrode and mechanically returns to the start position.

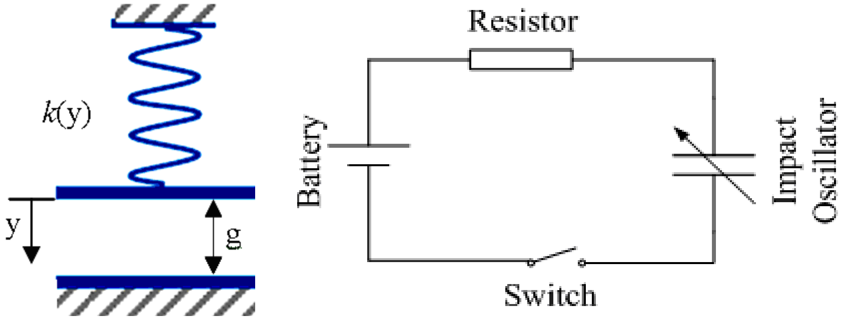

Fig. 1 (a) schematic view of the mechanical impact oscillator; (b) electrical circuit used to drive the impact oscillator

2.2. Mathematical model

The equation of motion of the movable plate is descried by Eq.1 and the charge and discharge process of the plate is governed by Eq.2. When the switch in fig 1b is turned on, the plate starts to charge and pull-in, eventually it will settle to an autonomous state.

$$my'' + \gamma y' + k_1 y + k_3 y^3 = F \qquad (1)$$

Where, $F = q^2 / 2\varepsilon A$

$$q' = (V_{dc} - q/C)/R \qquad (2)$$

Where, m, k_1 k_3, γ, ε, F, q, A, C and R are the effective mass, linear stiffness, cubic stiffness, damping coefficient, electric permittivity, the electrostatic force, electrical charge, area of the movable plate, capacitance of the moveable plate and resistance in the charging circuit.

2.3. Electrostatic pull-in

Considering a constant voltage applied between the parallel electrodes, the critical voltage to pull-in the resonator can be easily analyzed for a linear spring (k_3=0) and it has been well documented in the literature as descried in Eq.3 [4]. However, the geometrical nonlinearity of the structure will shift the pull-in voltage upwards. Fig.2a shows that the normalized relative pull-in voltage (ratio between the pull-in voltage with and without nonlinearity) depends upon the ratio k_1/k_3g^2 and the static equilibrium position of the resonator can go beyond one third of the gap. This can be used as a reference in designing a nonlinear capacitive resonator.

$$Vpi = (8kg^3 / 27\varepsilon A)^{1/2} \qquad (3)$$

2.4. Simulation results and discussion

The autonomous system was simulated by solving the coupled equations in the MatLab environment. A fourth order Runge-Kutta method was used to solve the ordinary differential equations (ODEs). The simulated structure is a 100µm×100µm Si_3N_4 resonator with small cubic nonlinearity (k_3=5.8e10N/m^3) suspending 3µm above the bottom electrode. The Fig.2b shows the transient motion of the resonator. It can be seen that the Si_3N_4 resonator was oscillating up and down, and the position where it was pulled down again depends on a match between the time constant of the electrical and mechanical systems. Furthermore, the simulation results from different driving power show that a higher external driving voltage will lead to a higher frequency of the system. Due to its nonlinear nature, the autonomous impact oscillator exhibits not only periodic but also chaotic behaviours [5].

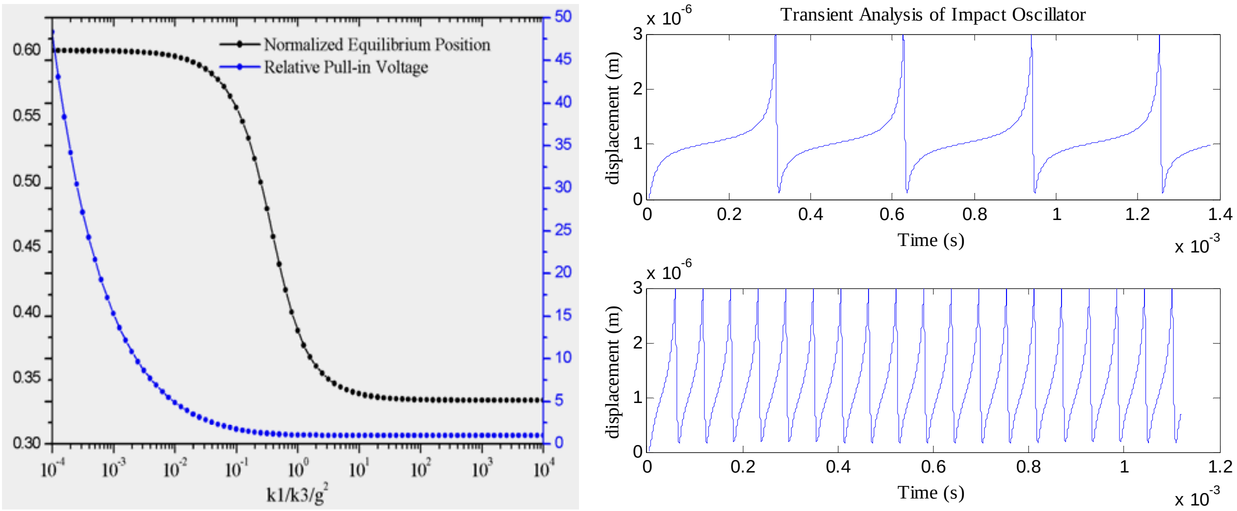

Fig. 2 (a) Effect of Cubic Nonlinearity on the Equilibrium Position and Pull-in Voltage; (b) Transient simulation of the autonomous system under different driving power (top: 1.02Vpi, bottom: 1.2Vpi)

3. Device fabrication

The device studied in this work includes a resonator and a bottom electrode as schematically shown in Fig.1. The fabrication process was accordingly carried out separately and introduced as follows.

3.1. Bottom electrode

The first five steps in Fig.3a shows the fabrication process of the bottom electrode. It started with pure silicon and it was oxidized at 1150°C for 10hrs in oxygen atmosphere. The thin SiO_2 film was used an insulating layer beneath the electrodes. After a standard cleaning process, a layer of SPR220-7 photoresist was spun at 2000rpm for 35s and soft-baked at 115°C for 3mins. Exposed at a dose of 700mJ/cm^2 and developed using MF26A for 4mins, the lift-off pattern was formed. A post baking was taken at 95°C for 45min to evaporate the solvent. Then, a Cr/Au film was deposited using thermally evaporated subsequently with a total thickness of about 150nm. The bottom electrode was left after stripping off the photoresist film. Finally, an insulating layer of SU8-2002 of 2µm thick was patterned on the substrate as a spacer, controlling the gap between the resonator and the bottom electrode. The major processing parameters are: spinning at 2000rpm for 30s, soft baking at 95°C for 5min, exposing for 18s using a Cannon mask aligner, post-exposure baking at 95°C for 3min. Fig.3b shows the digital image of the fabricated bottom electrodes.

3.2. Silicon nitride resonator

A commercially available Si_3N_4 membrane of 500nm thickness and 250µm side length was used. After a standard cleaning, it was coated with a Cr/Au layer of 100nm thick using a thermal evaporator (step 6 in Fig.3a). The coated Si_3N_4 membrane was then mounted on Revalpha 3195M thermal tape prior to FIB milling. A central plate with the size of 100µm×100µm and four supporting beams with size of 50µm×10µm were milled in a dual beam system

(Strata^{TM} DB235, FEI) with an ion beam current of 5nA. Fig.3c shows a SEM micrograph of the milled micro resonator. The fabricated Si_3N_4 resonator was assembled with the bottom electrode as shown by step 8 in Fig.3a. The Au coated resonator and the bottom electrical contact-pad were connected using a conductive paste. Fig.3d shows the assembled device and the testing is ongoing.

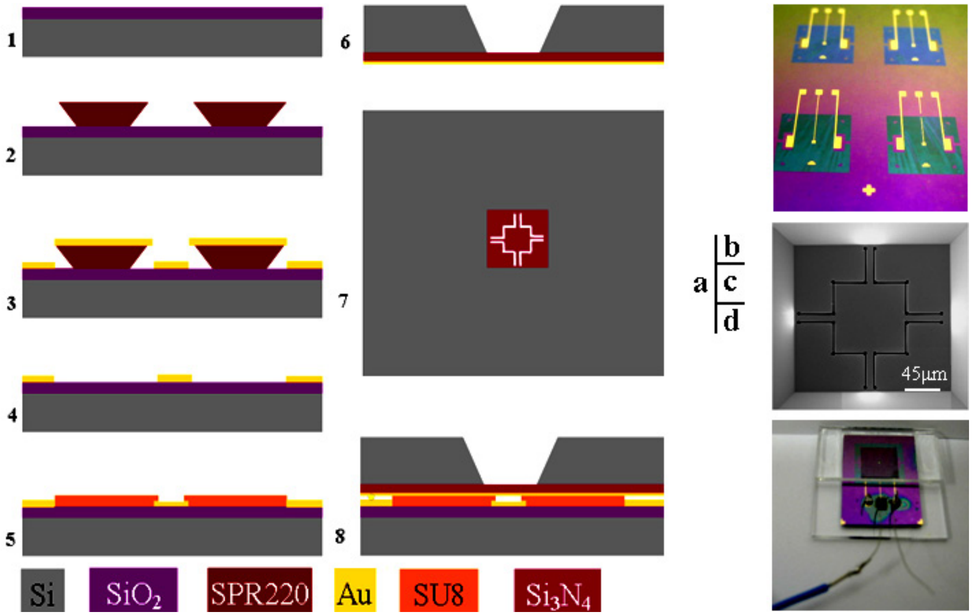

Fig. 3 (a) process of the device fabrication; (b) digital image of the fabricated bottom electrodes; (c) SEM micrograph of the Si_3N_4 resonator; (d) digital image of the assembled device

4. Summary

In this paper, an electrostatic impact oscillator was proposed and fabricated. The mechanical behavior of this device was numerically simulated. The effect of cubic nonlinearity of the structure on the static pull-in voltage and equilibrium position was reported. The simulation of this autonomous impact system also shows that the external voltage has a dramatic effect on its period.

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