PSi membranes based patterned MEMS resonator for biosensing applications

A S Bhattacharyya[1,2] and A K Rajak[1]

[1]Department of Nanoscience and Technology, Central University of Jharkhand
[2]Centre of Excellence in Green and Efficient Energy Technology, Central University of Jharkhand

October 23, 2023

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A.K. Rajak[1], A.S. Bhattacharyya[1,2 a)]

[1] Department of Nanoscience and Technology, Central University of Jharkhand, Ranchi 835205, India

[2] Centre of Excellence in Green and Efficient Energy Technology, Central University of Jharkhand, Ranchi 835205, India

[a)] Electronic mail: arnab.bhattacharya@cuj.ac.in ; 2006asb@gmail.com

ABSTRACT

Biosensors are an integral part of medical diagnostics. The materials, as well as the structural makeup used in these devices, are being upgraded through various solid-state processes, chemical processes, and micro-machining techniques. The material porous Silicon (PSi) has biosensing capabilities that can cause immobility of the attached biomolecules in its pores. The variation in porosity with current density was presented and related to the different etched stages of the silicon surface. PSi is a novel patterned cantilever MEMS resonator membrane that can be utilized for high-precision biosensing. Finite element modeling shows the strain distribution in the novel design. A theoretical base of the coupled oscillations in the sensors for the difference in dimension separation and absorbance was given.

Keywords: Porous Silicon, biosensors, MEMS resonator

I. INTRODUCTION

Biosensors are being upgraded in medical diagnostics implants either with the inclusion of new materials or by making an improved design for better sensibility and faster output[1]. Biocompatibility is also a major issue when applying these devices to the human body. Porous Silicon (PSi) has been used as a biosensor in recent years. Due to its porosity, the captured biomolecules are immobilized which helps in better sensing[2, 3]. Because porous silicon (P-Si) has the ability to immobilise biological molecules, it can be utilised as a biosensor. Variations in etching parameters during the electrochemical synthesis of P-Si caused changes in Si surface morphology, which caused changes in porosity and refractive index, boosting their utility in sensing and optical communication. Novel P-Si-based biosensors for nucleic acid detection and mass transport concerns were proposed. It could also be used to address the issue of antibody cross-reactions, which cause low RT-PCR sensitivity[4].

Cantilever-shaped MEMS resonators although a high precision sensing system, suffer the problem of mass sensitivity. A novel patterned PSi membrane (PSiM) micro sensing device has been envisaged in this communication which takes care of all the above-mentioned issues. The deconvolution of the combined signals coming out of the device has also been discussed.

II. EXPERIMENTAL

PSi was made in an electrochemical bath consisting of HF as an electrolyte. The P-type Si wafer (100) was anodized in the formation bath containing HF: C_3H_7OH in a 1: 1 ratio. The silicon chip gets etched away in this process leading to the formation of pores. The etching times and the current densities are used to influence the pore dimensions. There are other different methods of synthesizing porous silicon[4, 5].

III. RESULTS AND DISCUSSIONS

A. PSi formation and porosity variations

An SEM image of the PSi surface showing the formation of pores is given in **Fig 1**. The porosity affects the refractive index of the material and Effective optical thickness (EOT) is the parameter used in the detection of analytes on the PSi surface which is again related to the refractive index. The effective refractive index of PSi (n_{PSi}) is a function of the refractive index of silicon (n_{Si}) and the pore filling material (n_{pore}). On absorbing a biomolecule, there is a change in the n_{pore} value which is initially 1 (for air)[3].

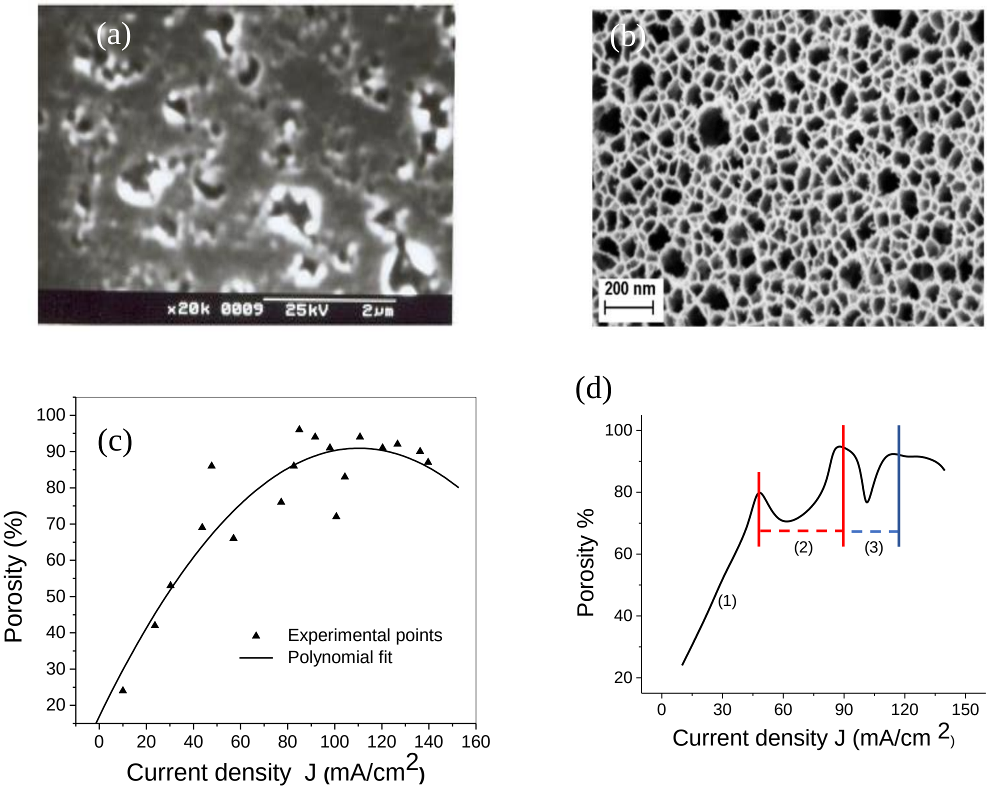


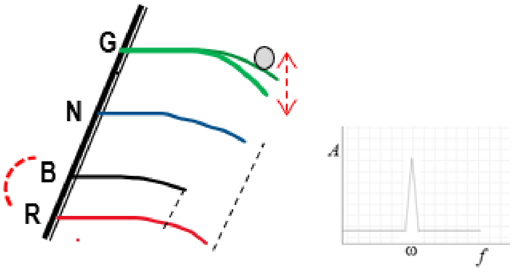
FiG 1. a) SEM image of PSi surface[3] b) top layer porous silicon membrane with average pore size is ~41 nm, with a standard deviation of ~20 nm[5]**.** (c) Variation of porosity % with current density[3] (d) the different stages of PSi formation

The porosity % was found to increase with current density in stage (1) as increased J led to enhanced etching of the Si surface. The sudden dip observed in stage (2) is due to the etching away of the top Si surface completely and the initiation of etching in the underneath Si region. The porosity increased with current density due to an increase in etching in stage 2 similar to the stage (1) after hitting a minimal. The whole process got repeated in stage (3) as well. However, the interesting observation was the transformations were much more rapid as observed with a much sharper dip. The reason behind this observation is because localized etching phenomena becoming predominant and also the pore growth branching starts to take place which can be explained with the help of Monte-Carlo Simulations where the probability of vertical pore growth is associated with a random number between 0 and 1, where 1 corresponds to absolute vertical growth and 0 corresponds to lateral growth[6].

B. PSi membrane-based cantilever MEMS resonators

PSi has biosensing applications. The pores give immobility to the absorbed materials giving better sensitivity. The PSi biosensors however suffer a limitation in sensitivity due to hindered diffusion of the absorbed biomolecules. The solution to which comes in the form of free-standing PSi membranes

(PSiMs)[7]. These free-standing PSiMs can act as transducers and can be fabricated over the surface of MEMS resonator sensors. Synchronized oscillations take place in these systems with coupling overhangs as micromechanical elements[8]. However, the coupled oscillations may vary based upon the dimension, separation, and capture of biomolecules on the PSiMs. A longer membrane oscillates at a lower frequency, whereas a capture of a biomolecule enhances the frequency of oscillation. The separation between two adjacent cantilevers is also an important factor when dealing with coupled oscillations. An illustration depicting all these effects is given in **Fig 2** where cantilevers are placed with different sizes, separation, and absorbance.



Effect due to	$\omega_{coupled}$	*Parameters*
dimension	$(\omega_{R+}\omega_B)/2$	-
separation	$(\omega_{R+}\omega_N)/k2$	*k, separation factor*
absorption	$(\omega_{N+n}\omega_N)/2$	*n, weight factor*

FIG 2. Coupling of cantilever PSiMs with different dimensions, separation, and absorbance

The Cantilever PSiMs were marked R (red), Black (B), Navy blue (N), and Green (G). The R and B cantilevers show the effect of the difference in dimensions; R and N show the effect of separation and N and G show the effect of absorbance, The coupled frequency for each of these cases is shown in a tabular form in the figure. The separation factor reduces the average frequency. The absorbance of a biomolecule enhances the frequency which helps in sensing.

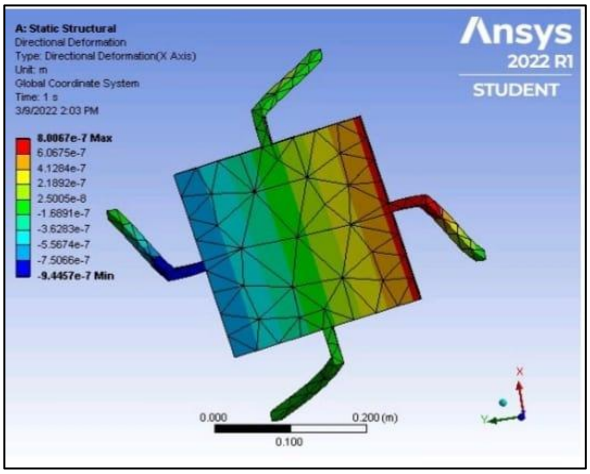


FIG 3. FEM model of a novel pedestal cantilever structure with directional deformation strain[9,10]

This PSi M-based cantilever mems resonator with a free end will again have an inherent problem of mass sensitivity as biomolecules absorbed close to the edges will cause higher intensity oscillations compared to the ones which are adsorbed close to the fixed end. This problem has been addressed by a novel design pedestal structure proposed by N Kim[9]. A finite element modeling of the structure with directional deformation strain is shown in **Fig 3**. A strain distribution model has been reported earlier according to which, increasing porosity causes strain relaxation in the amorphous domains and strain build-up in the crystalline ones. A single large membrane may not be mechanically stable due to a higher amount of strain and may break heavier biomolecules. The patterned structure as shown below (**Fig 4**) with insulating SiO_2 as the pedestals will be devoid of this problem.

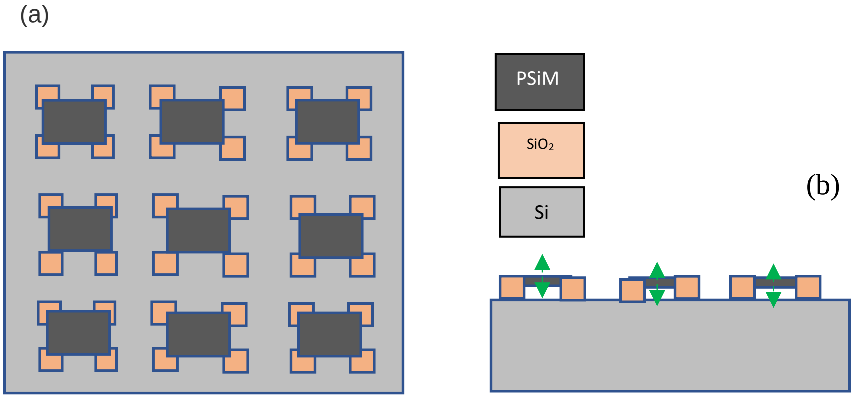


FIG 4. Patterned Cantilever MEMS resonator developed on Si (a) Top-view (a) cross-sectional view

Biomolecule attachment to pore walls results in a shift in reflectance spectrum, which is utilised to identify high-risk human papillomavirus 16 and 18 linked to the development of precancerous and cancerous lesions[11]. P-Si microcavity fluorescence images is also used for the detection of gibberellins which are used in crops and whose excessive amount is toxic for humans[12].

PSi-based biosensors assess the current intensity brought about by an enzyme immobilised on the electrode surface acting in a redox reaction on the target analyte. PSi is significant because it improves sensitivity and has a larger surface area than flat electrodes. The primary challenge with these biosensors is caused by the poor conductivity in PSi when compared to metal electrodes. To get around this, PSi can be coupled with a thin film of Pt, Au, or conductive polymer to increase its conductivity[13]. The photoluminescence lifetime, defined as 1/e times the initial intensity, decreased as emission energy increased. The photoluminescence lifetimes τ changes due to the existence of more than one luminescence centres due to absorption of biomolecules in the pores.

IV. CONCLUSIONS

The different stages of porosity variation associated with current density during the formation of PSi were shown. The sensing ability of Porous Silicon (PSi) was discussed with a novel design of a pedestal cantilever MEMS resonator. The coupled frequencies for the difference in dimension, separation, and absorbance were discussed. Finite element modeling was done to show the directional deformation strain.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the help of Dr S. M. Hossain, IIEST Howrah for experimental studies

CONFLICT OF INTEREST

The authors have no conflicts to disclose.

ETHICS APPROVAL

This work has not been submitted to any other journal

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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