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Finite element analysis of polymer-encapsulated ZnO nanowire-based sensor array intended for pressure sensing in biometric applications

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Abstract

This work presents results of finite element analysis of an array of ZnO nanowires with bottom-bottom electrode configuration, which are integrated onto a multi-layer chip stack and encapsulated within a polymer. The dynamically-deformed array constitutes a representative part of a high-resolution pressure sensor intended for reliable identification of the smallest fingerprint features such as shape of the ridges and pores. Parametric study was performed in order to predict the most rational values of the Young's modulus and thickness of the encapsulation layer in terms of magnitude and variability of the piezoelectric signals. The results also demonstrate the impact of nanowire aspect ratio and load orientation on the generated electrical signals.

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Keywords: ZnO; piezoelectric nanowires; pressure sensor; finite element model; piezoelectric signals; polymer encapsulation; Young's modulus

1. Introduction

Piezoelectric nanostructures in the form of nanoparticles, nanorods, nanowires, nanowalls, nanotubes, nanofibers or nanofilms have been extensively studied in recent years with the aim of implementing them as transducers in optical, chemical, biological, gas, temperature, humidity, strain, force or pressure sensing applications [1-2]. The most widely used piezoelectric nanomaterials include semiconducting wurtzite compounds (e.g. ZnO, GaN, InN, CdS), ferroelectrics (e.g. PZT, $BaTiO_3$, $NaNbO_3$, $LiNbO_3$), piezoelectric polymers (e.g. PVDF) and nanocomposites. In particular, the last 10 years have witnessed an upsurge of research activity on ZnO nanostructures.

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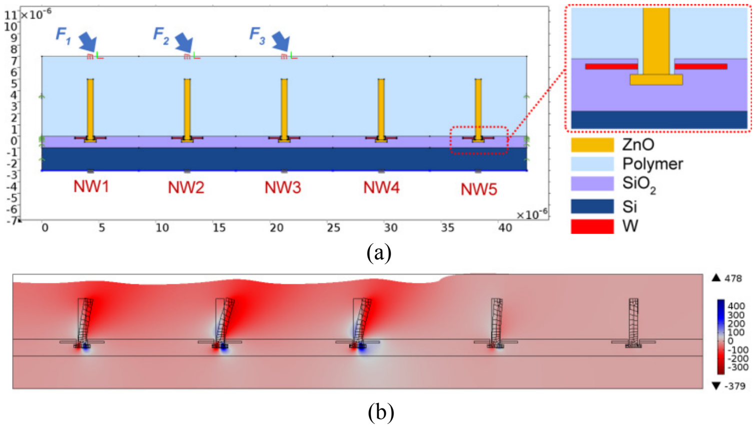

Fig. 1. (a) COMSOL model of the periodic array of ZnO NW-based piezo-pixels encapsulated in PMMA-based polymer (each NW has two tungsten electrodes at the root that are connected to an external capacitor C_{ext} = 10 fF). NW dimensions: width w_{NW} = 0.5 µm, height h_{NW} = 5 – 15 µm, inter-NW gap d_{NW} = 8 µm. (b) Distribution of electric potential in the deformed sensor array (side bar – in mV), which was obliquely loaded with pressure load $F_h = F_v$ = 1 MPa (w_{NW} = 0.5 µm, h_{NW} = 2.5 µm, height of polymer layer (cap) above the NWs h_{pol} = 1.5 µm).

Stand-alone or arrayed nanorods and nanowires (NWs) constitute an attractive ultralow-power high-resolution strain, force or pressure sensing technology, which is targeted for different applications such as e-skin [3] or fingerprint scanning [4]. It is expected that further advancements in the field of individually-addressable piezoelectric NWs and their arrays could lead to the development of next-generation compact fingerprint sensors of very high spatial resolution (several thousand dpi), which would offer reliable detection of the smallest fingerprint features such as the shape of the ridges and sweat pores [5].

Piezoelectric NW arrays have to be encapsulated in a polymeric medium, which serves the dual purpose of force transfer and physical protection. The key challenge in development of encapsulated NW-based fingerprint sensors is to identify a (co)polymer with a suitable blend of mechanical and physico-chemical properties, ensuring both high sensitivity to minute load variations and proper protection against mechanical damages and external contamination. Therefore, determination of the appropriate Young's modulus of the encapsulant is important. An overly hard polymer would degrade force transfer, thereby reducing electrical output, while very soft one would compromise sensor robustness. In addition, tuning the thickness of the encapsulation layer is required in order to maximize the output and minimize spurious signals induced by the effects related to mechanical crosstalk.

This paper reports on finite element (FE) analysis of a dynamically-loaded encapsulated array of 5 piezo-pixels – vertical ZnO NWs with bottom-bottom (side) electrodes connected to the external capacitors – in order to predict the near-optimal values of the Young's modulus (E_{pol}) and thickness of the polymer layer above the NWs (cap height – h_{pol}). Reported numerical results also demonstrate the influence of NW aspect ratio (AR_{NW}) and load orientation on the electrical responses.

2. Finite element analysis of the encapsulated ZnO nanowires with bottom-bottom electrode configuration

COMSOL Multiphysics® was used to implement a 2-D FE model of the PMMA-encapsulated ZnO NW-based pressure sensing array, which includes 5 piezo-pixels and the associated chip stack layers (Fig. 1). *Piezo-pixel* refers here to a piezoelectric NW that is connected to an external capacitor (C_{ext} = 10 fF) [6]. The piezo-pixel is configured so as to collect charges through tungsten side electrodes located at the root of the NW, which is in contrast to the conventional top-down contacting configuration [7]. The top of the encapsulation layer is subjected to downward ramping load that imitates pressing with a fingertip [6]. It is assumed that the array is loaded by a fingertip region corresponding to a ridge edge, i.e. the ridge presses NW1, NW2 and NW3, while the remaining NW4 and NW5 are not directly loaded. Outputs of these unloaded NWs are considered to be spurious signals that would degrade sensor resolution. Therefore, the design targets for the case of equal load $F_1 = F_2 = F_3$ are: i) to maximize mean voltage ($V_m = (V_{NW1} + V_{NW2} + V_{NW3})/3$) and minimize standard deviation (σ_V) [7]; ii) to minimize spurious signals (V_{NW4}, V_{NW5}).

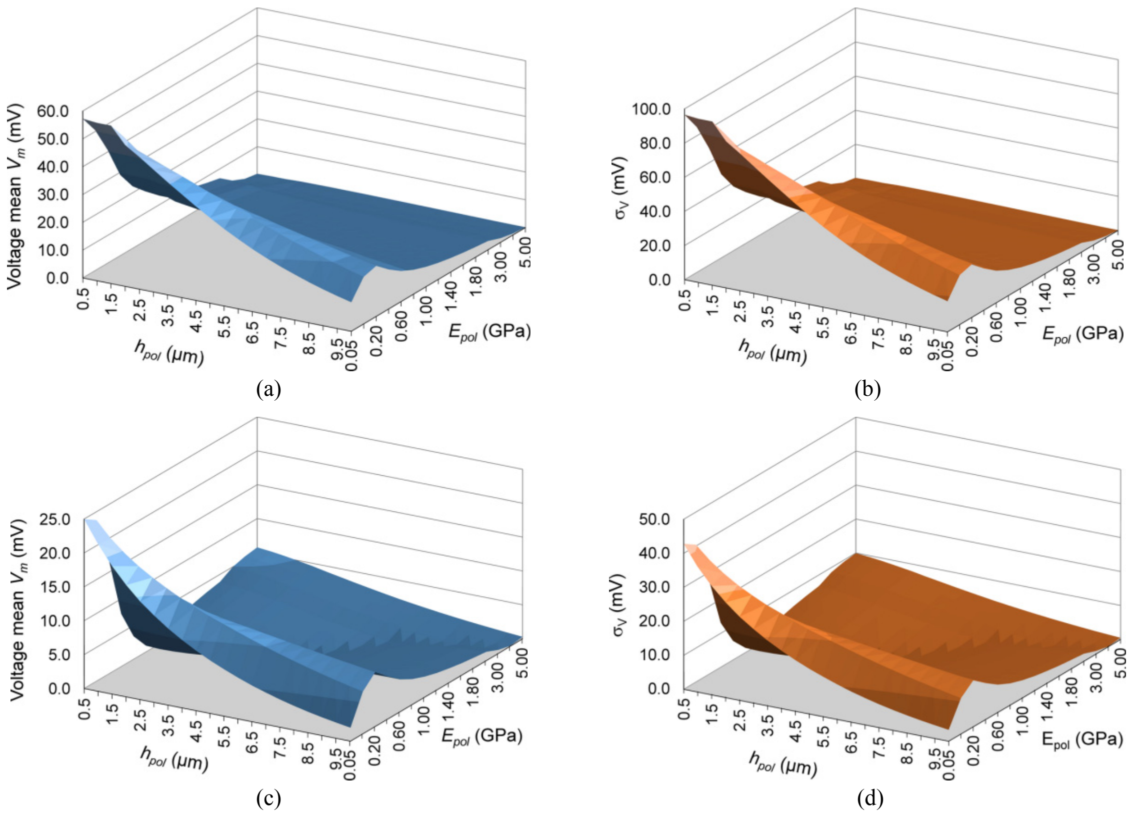

Fig. 2. Surface plot of the average voltage outputs V_m and their variability σ_V as a function of polymer cap height and Young's modulus for the case of oblique load $F_h = F_v = 1$ MPa for: (a)-(b) $AR_{NW} = 5$ ($w_{NW} = 0.5$ µm, $h_{NW} = 2.5$ µm); (c)-(d) $AR_{NW} = 30$ ($w_{NW} = 0.5$ µm, $h_{NW} = 15$ µm).

Parametric study was performed in order to determine the near-optimal values of E_{pol} and h_{pol} by examining surface plots, which were constructed for the cases of low and high aspect ratio NWs when the array is deformed by pressure load of different orientation (Figs. 2-3). Here, the term *near-optimal* implies the highest V_m accompanied by the lowest possible σ_V. Comparison of Fig. 2(c-d) and Fig. 3 indicates strong dependence of V_m and σ_V on the load orientation: i) more complex variation of V_m and σ_V is observed with changing E_{pol} and h_{pol} when horizontal load component is introduced; ii) the variation trends are opposite for the vertical and oblique loading cases, i.e. in the latter case the values of V_m and σ_V increase with larger h_{pol} and they also increase when $E_{pol} > 0.2$ GPa and in the former case – the outputs rapidly decrease with larger h_{pol} (for softer polymer) and they are strongly reduced when $E_{pol} > 0.2$ GPa. Furthermore, the plots in Fig. 2 reveal that increase in NW aspect ratio also leads to a more complex variation of V_m and σ_V with changing E_{pol} and h_{pol}. The observed complex dependence on the load orientation makes it challenging to unambiguously identify the near-optimal values of E_{pol} and h_{pol} since the character of the pressure load in real life will change from person to person. Thus, the recommendation for the near-optimal values is based on the assumption that in majority of cases there will be at least some horizontal load component during the actual fingerprint sensor usage. Therefore, in order to be on the safe side the recommended values of near-optimal E_{pol} and h_{pol} are about 0.2 GPa and 2 – 4 µm, respectively. It should be noted that the values for h_{pol} are the same as for the case of piezo-pixels with conventional top-bottom electrode configuration. Meanwhile, the recommendation to use $E_{pol} \approx 0.2$ GPa is more stringent in the current case since for the top-bottom configuration the voltage outputs are essentially insensitive to increasing E_{pol} within the wide range of ~0.1 – 1 GPa [7].

Comparison of outputs generated at near-optimal E_{pol} and h_{pol} by the NW array having different electrode configurations demonstrates that the bottom-bottom configuration outperforms the top-bottom one, i.e. at $AR_{NW} = 30$

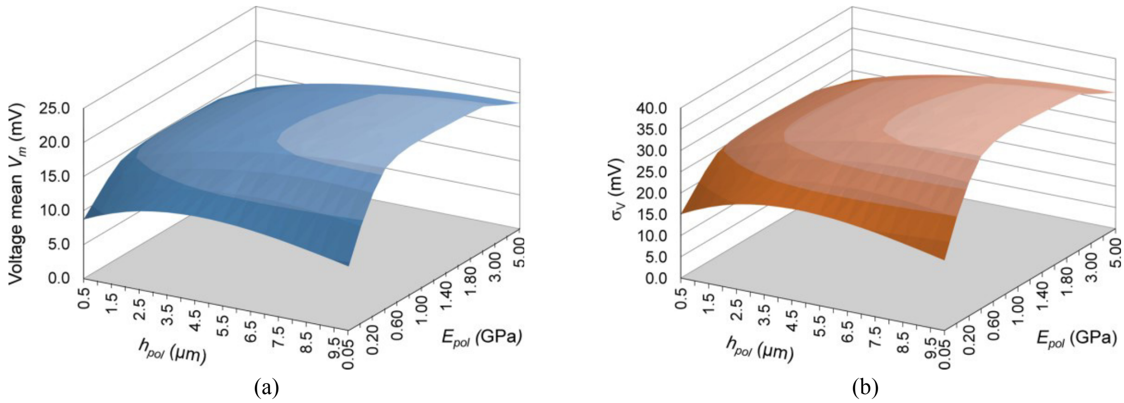

Fig. 3. Surface plot of the average voltage outputs V_m and their variability σ_V as a function of polymer cap height and Young's modulus for the case of pure vertical load F_v = 1 MPa for AR_{NW} = 30 (w_{NW} = 0.5 µm, h_{NW} = 15 µm).

the average voltage is larger about 2 times both for the vertical and oblique ($F_h = F_v$) loading cases. At AR_{NW} = 5 the increase in V_m reaches ~15 times for the oblique loading case. The largest distinction between the two configurations is the considerably larger variability of voltage outputs generated by the equally loaded NW1, NW2 and NW3 in the case of bottom-bottom configuration (even under pure compression as evident in Fig. 3(b)).

3. Conclusion

This paper reported on multiphysics finite element analysis of the encapsulated periodic array of ZnO nanowire-based piezo-pixels with bottom-bottom electrode configuration. Results of the parametric study demonstrate that a softer polymeric layer ($E_{pol} \approx 0.2$ GPa) of relatively low thickness ($h_{pol} \approx 2 - 4$ µm) is preferred for the encapsulation of the array if one attempts to maximize sensor signals that are generated under oblique pressure load with vertical component being the predominant one. Reported numerical results also suggest that due to the pronounced variability of the voltage signals generated by the individual nanowires, the piezo-pixels with bottom-bottom electrodes may yield lower native resolution of a fingerprint sensor. Therefore, additional simulation-assisted design efforts should be dedicated in the future for examining this issue more thoroughly.

Acknowledgements

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