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ZnO Nanowire Embedded Graphene Aerogel Structures for Piezotronics Strain Sensor/Nanogenerators for Health Monitoring

Onur Ergen*

Department of Electrical and Electronics Engineering, Koc University, Istanbul, Turkey

ABSTRACT

Artificial Intelligence (AI) and Machine Learning (ML) lead a new era in remote health monitoring and preventive care, while making ZnO based strain sensor and nanogenerators a very attractive data collection tool. Here, we demonstrate flexible piezotronics strain sensor/nanogenerator, based on ZnO nanowires embedded on graphene aerogels. The I-V characteristic of the sensor shows high sensitivity due to desirable piezotronics properties, piezopotential modulated changes in Schottky barrier height, under both static and dynamic loads. A good gauge factor of as high as 120 has been demonstrated, which is almost 50% higher than the gauge factor reported for any ZnO/carbon based strain sensors.

Keywords: Nanogenerator; Wearable electronics; Strain sensor; Piezotronics; Piezoelectric; Sensors; ZnO nanowires; Aerogels; Graphene; Health monitoring

INTRODUCTION

With the rise of Artificial Intelligence (AI) and Machine Learning (ML) techniques, flexible piezotronics strain sensors and nanogenerators are a very attractive tool for data collection, especially with remote health monitoring and preventive care [1]. Their high sensitivity and fast response times makes them an ideal candidate for effective data collection for these important applications, especially, since their nanostructured architectures have become very intriguing to researchers due to the potential benefit of flexibility, energy harvesting capability and easy deployment. Various nano-architectures have been designed and fabricated from many different piezoelectric materials. Among these piezoelectric materials, a large number of applications use ZnO nanomaterials, due to its unique advantages, such as biocompatibility, low cost, easy synthesis and optical properties. Especially ZnO, which received great attention after wang's group ZnO nanowire based nanogenerator formation, that demonstrated excellent strain induced response properties [2]. Thus, ZnO nanowires (ZnO-NWs) have become a center of attention in building high sensitive strain sensors.

However, ZnO-NWs requires compatible host materials that are electronically coupled with ZnO and allow flexible adaptive movements. Because, without the proper host material, ZnO-NWs can be very brittle and not suitable for flexible applications, especially under stress, ZnO layer is more prone to cracking and failure. Thus, ZnO-NWs is constantly embedded in various different materials to build flexible strain sensors, including different carbon fiber, carbon paper, polymer composite materials, etc.

MATERIALS AND METHODS

In this paper, we present the fabrication and application of a flexible piezotronics strain sensor/nanogenerator, architecture based on ZnO-NWs, embedded in Graphene Aerogel (GA). The strain sensor fabricated with CVD grown ZnO-NWs film on a graphene aerogel substrate and strain sensing, both static and dynamic loading, are demonstrated [3]. The I-V behavior of the device showed high sensitivity with a Gauge Factor (GF) of as high as 120, which is almost 50% higher than GF reported ZnO/carbon based strain sensors (Figure 1).

Correspondence to: Onur Ergen, Department of Electrical and Electronics Engineering, Koc University, Istanbul, Turkey; E-mail: oergen@ku.edu.tr

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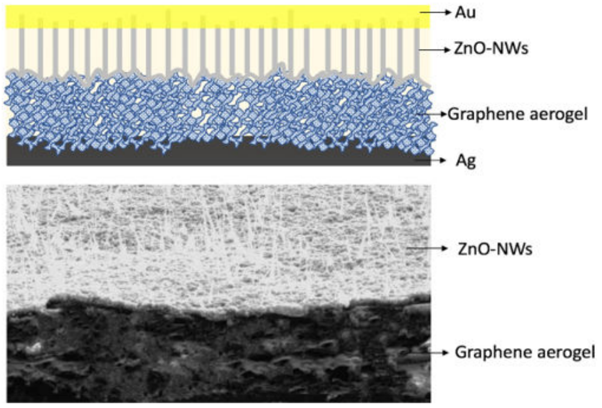

Figure 1: The schematic diagram ZnO-Nws/GA piezotronics strain sensor. The cross sectional SEM image of the ZnO-Nws/GA.

GO was suspended (2 wt%) in Deionized (DI) water and sonicated at ~40 kHz. Then, in a glass vial, 5 ml of the GO suspension was mixed with 500 µL of concentrated NH_4OH (30%). This solution was then transferred to a glass slide attached to rubber rectangular molds and cured in an oven at 80°C for 72 h. The resulting gels were removed from the molds and subject to chemical exchange with acetone and DI water, followed up by super critical CO_2 drying and pyrolyzed, carbonized, at ~1000°C under a N_2 atmosphere for 3 h. Resulted GA materials were then mixed with a ZnO nanoparticle (ZnO-Nps) solution [4].

The characterization of the I-V behavior of the strain sensor was investigated under static loading, shown in Figure 2. At different strains, Schottky Barrier Height (SBH) and current values in rectifying curves alters, shift upward and downward with compressive and tensile strain, respectively [5].

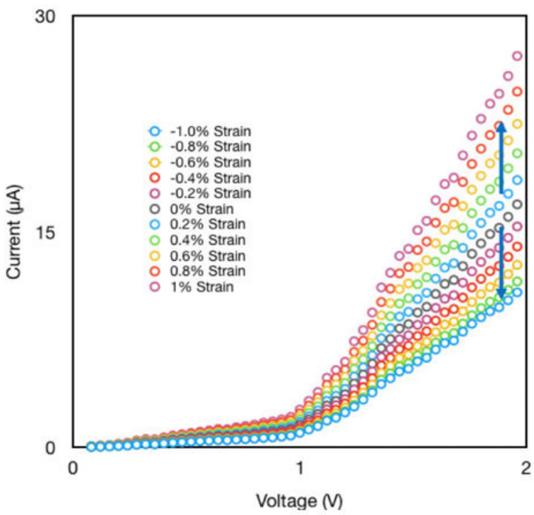

Figure 2: I-V characteristic of the strain sensor at different strain.

The stability of the device was tested with many repeated full cycles of compressing and stretching, at a frequency of 2 Hz under a fixed bias of 1V (Figure 3). It can be clearly seen that the current reaches approximately the same values in each cycle, which indicate a stable behavior and desirable electron transport behavior, due to good schottky junction formations [6].

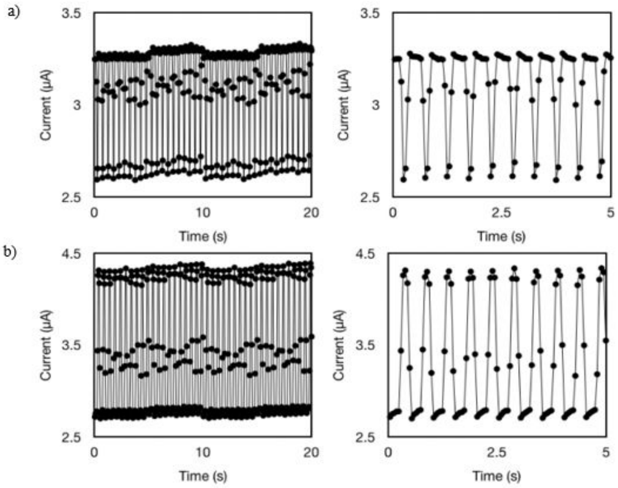

Figure 3: Current response of the strain sensor (a) compressed, (b) stretched at a frequency of 2 Hz under fixed bias 1 V.

RESULTS AND DISCUSSION

The schematic of the strain sensor device and SEM image is shown in Figure 1. Graphene aerogels are synthesized by the gelation of a Graphene Oxide (GO) suspension. GO was suspended (2 wt%) in Deionized (DI) water and sonicated at ~40 kHz. Then, in a glass vial, 5 ml of the GO suspension was mixed with 500 µL of concentrated NH_4OH (30%). This solution was then transferred to a glass slide attached to rubber rectangular molds and cured in an oven at 80°C for 72 h. The resulting gels were removed from the molds and subject to chemical exchange with acetone and DI water, followed up by super critical CO_2 drying and pyrolyzed, carbonized, at ~1000°C under a N_2 atmosphere for 3 h. Resulted GA materials were then mixed with a ZnO nanoparticle solution (<100 nm) which is a very important step to produce high quality ZnO-NW/GA interfaces, while ZnO nanowires are being synthesized with Chemical Vapor Deposition (CVD) vapor trapping method. Finally, the whole device architecture was developed with contacts, Au for ZnO and Ag for GA and encapsulated with Polydimethylsiloxane (PDMS) elastomer, which is very important to stabilized GA interconnected flakes [7].

The characterization of the I-V behavior of the strain sensor was investigated under static loading, shown in Figure 2. At different strains, Schottky Barrier Height (SBH) and current values in rectifying curves alters, shift upward and downward with compressive and tensile strain, respectively. The stability of the device was tested with many repeated full cycles of compressing and stretching, at a frequency of 2 Hz under a fixed bias of 1 V. It can be clearly seen that the current reaches approximately the same values in each cycle, which indicate a stable behavior and desirable electron transport behavior, due to good schottky junction formations [8]. We also tested the transient decay of electrons at a fixed strain, strain sensors stretched for 100 s and then released for 10 s repeatedly.

It can be clearly seen that strain sensor quickly recover to initial conditions once the stretch registered. The decay during the hold is due to ZnO-Nps charge trapping behavior which is widely reported in the literature [9]. This experiments also clearly shows that graphene aerogel is a good host material to accommodate ZnO-Nps, which commonly have cracking and adhesion problem during dynamic loading. GA enables continuous active contact to ZnO at any loading condition due to its flexibility and high porous structure. The response of the sensor was also studied under dynamic loading (Figure 4), measured at 0.1 Hz, 1 Hz and 2 Hz. As it can be seen, frequency of the excitation follows frequency of the response, without drift and amplitudes increase with frequency, which indicates high sensitivity for both tension and compression. We also tested the transient decay of electrons at a fixed strain, strain sensors stretched for 100 s and then released for 10 s repeatedly. It can be clearly seen that strain sensor quickly recover to initial conditions once the stretch registered. The decay during the hold is due to ZnO-NWs charge trapping behavior which is widely reported in the literature. This experiments also clearly shows that graphene aerogel is a good host material to accommodate ZnO-NWs, which commonly have cracking and adhesion problem during dynamic loading. GA enables continuous active contact to ZnO at any loading condition due to its flexibility and high porous structure. It should be noted that during the high strain ZnO film, which support ZnO nanowires, can slightly crack, but this does not affect electronic performance because current paths develop through nanowires [10].

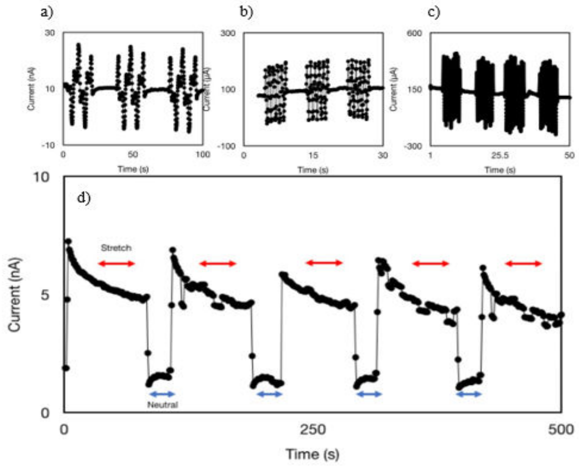

Figure 4: Dynamic response of the strain sensor at a frequency of a) 0.1, b) 1 and c) 2 Hz. d) time dependent piezo electiric effect repeated cycle.

Figure 5 shows the derived change in SBH based on the thermionic emission-diffusion model, as a function of stain at bias of 1 V and 2.0 V, with calculation method as in reference. Also, logarithm plot of the current, at fixed bias of 1 V and 2 V, as a function of strain is linearly change with the applied strain, which is very consistent with previous reports and ensures reliability of the device [11]. To determine the performance of the strain sensor, gauge factor is calculated 120 by the equation GF=(ΔR/R)/Δε, where R is the initial resistance, ΔR is the changed resistance and Δε is the strain change. This calculated value is much higher than values reported for ZnO/carbon based strain sensors, 1.5 times higher than ZnO-carbon nanofiber strain sensors (GF=81) and almost 6 times higher than ZnO/paper composite strain sensors (GF=21.12). The image of the LED turning on and off, during directional motion. PET/ITO/Cu is used to induce a schottky rectification effect on ZnO nanowires while sponge like GA structure is helping ZnO nanowires respond in a controlled and reversible way [12].

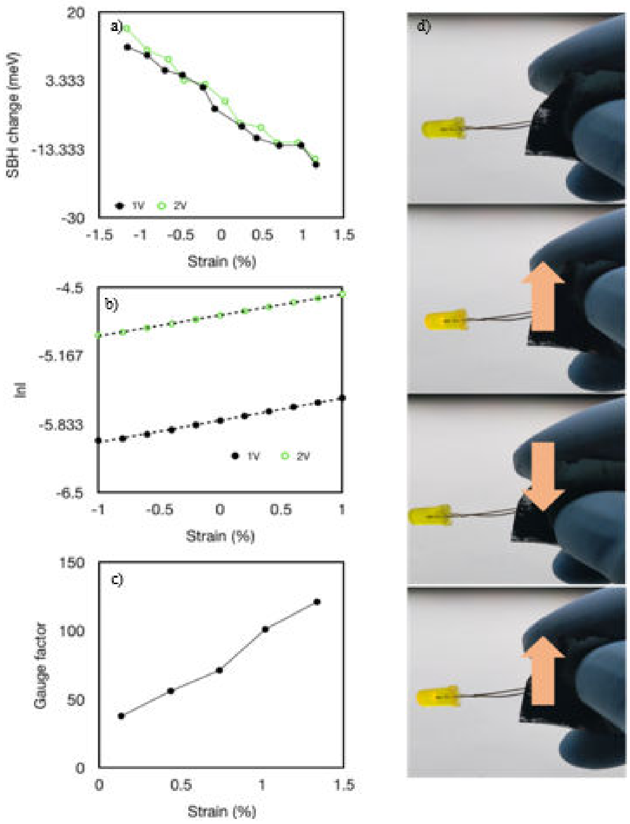

Figure 5: a) The derived change in SBH based on the thermionic emission-diffusion model, as a function of strain, b) Plot of In I *vs.* strain at a drain-source bias of 1 V and 2 V respectively, c) Image of the LED turning on and off with respect to directional motion. d) A PET/ITO/Cu is used to induce a Schottky rectification effect in the circuit.

CONCLUSION

In summary, we demonstrated a technique to produce cost effective flexible piezotronics strain sensor based on ZnO nanowires grown on graphene aerogel substrates. Graphene aerogels provides excellent receiving substrate properties that ZnO piezoelectric properties can be maintained under any strain conditions. I-V characteristic of the device demonstrates consistent SBH modulation and high sensitivity under static and dynamic loading. Moreover, it exhibits very good gauge factor, flexibility and stability that indicates this device can be used remote health monitoring and preventive medicine.

This device can be used with various healthcare applications such as remote health monitoring, preventive medicine and diagnosis.

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