

## Strain sensing skin-like film using zinc oxide nanostructures grown on PDMS and reduced graphene oxide

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**Abstract.** In this paper, we present a strain-sensitive composite skin-like film made up of piezoresistive zinc oxide (ZnO) nanorods embedded in a flexible poly(dimethylsiloxane) substrate, with added reduced graphene oxide (rGO) to facilitate connections between the nanorod clusters and increase strain sensitivity. Preparation of the composite is described in detail. Cyclic strain sensing tests are conducted. Experiments indicate that the resulting ZnO-PDMS/rGO composite film is strain-sensitive and thus capable of sensing cycling strain accurately. As such, it has the potential to be molded on to a structure (civil, mechanical, aerospace, or biological) in order to provide a strain sensing skin.

**Keywords:** strain sensing; flexible; skin; poly(dimethylsiloxane); reduced graphene oxide; zinc oxide

### 1. Introduction

Dynamic monitoring of structural strain is fundamental to structural health monitoring and maintenance during extreme events (Nagarajaiah and Erazo 2016). Problematically, industry-standard resistance-based foil strain gages measure strain unidirectionally and locally, limiting their utility for large-scale monitoring. To facilitate such distributed monitoring, recent research has explored alternative materials with inherent strain sensing properties (Li *et al.* 2004, Dharap *et al.* 2004, Withey *et al.* 2012, Sun *et al.* 2015, 2016). Piezoelectric materials such as zinc oxide (ZnO) have attracted considerable interest due to their ability to transduce mechanical strain into electrical signals with minimal power requirements (Park *et al.* 2008). Such materials are capable of sensing strain, but are unsuitable for standalone use, as they are typically highly brittle (Klingshim *et al.* 2010). Researchers have found rGO—reduced graphene oxide—thin films (Loh *et al.* 2010, Trung *et al.* 2014, Tang *et al.* 2015) to be effective strain sensors. The possibility of combining ZnO and rGO for strain sensing is investigated in this study.

In order to be utilized in strain sensing, piezoelectric materials must be supported by a scaffold. Previously, we demonstrated a low-temperature solvo-thermal method to fabricate ZnO nanorods on a cellulose scaffold, and demonstrated that the final construct constituted an accurate, flexible, low-cost strain sensor (Gullapalli *et al.* 2010). However, the nature of the cellulose scaffold made

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1641-1646.

- Klingshirn, C.F., Bruno K.M., Andreas W., Axel H. and Johannes M.G. (2010), *Zinc Oxide: From Fundamental Properties Towards Novel Applications*, Springer, New York City, NY, USA.
- Li, Z., Dharap, P., Nagarajaiah, S., Barrera, E. and Kim, J. D. (2004), "Carbon nanofilm sensor", *Adv. Mater. J.*, **16**(7), 640-643, DOI: 10.1002/adma.200306310.
- Loh, K.P., Bao, Q., Eda, G. and Chhowalla, M. (2010), "Graphene oxide as a chemically tunable platform for optical applications", *Nature Chemistry*, **2**(12), 1015-1024, doi: 10.1038/nchem.907.
- Nagarajaiah, S. and Erazo, K. (2016), "Structural monitoring and identification of civil infrastructure in the United States", *Struct. Monit. Maint.*, **3**(1), 51-69, DOI: 10.12989/smm.2016.3.1.051.
- Park, G., Rosing, T., Todd, M.D., Farrar, C.R. and Hodgkiss, W. (2008), "Energy harvesting for structural health monitoring sensor networks", *ASCE J. Infrastruct. Syst.*, **14**, 64-79.
- Sun, P., Bachilo, S., Weisman, M. and Nagarajaiah, S. (2015), "Carbon nanotubes as non-contact optical strain sensors in smart skins", *J. Strain Anal. Eng. Des.*, **50**(7), 505-512, DOI: 10.1177/0309324715597414.
- Sun, P., Bachilo, S.M., Nagarajaiah, S. and Weisman, R.B. (2016). "Toward practical non-contact optical strain sensing using single-walled carbon nanotubes", *ECS J. Solid State Sci. Technol.*, **5**(8), M3012-M3017, DOI: 10.1149/2.0031608jss.
- Tang, Y., Zhao, Z., Hu, H., Liu, Y., Wang, X., Zhou, S. and Qiu, J. (2015), "Highly stretchable and ultrasensitive strain sensor based on reduced graphene oxide microtubes-elastomer composite", *ACS Appl. Mater. Interfaces*, **7**, 27432-27439, doi: 10.1021/acsami.5b09314.
- Trung, T.Q., Tien, N.T., Kim, D., Jang, M., Yoon, O.J. and Lee, N.E. (2014), "A flexible reduced graphene oxide field-effect transistor for ultrasensitive strain sensing", *Adv. Funct. Mater.*, **24**, 117-124.
- Withey, P.A., Vemuru, V.S.M., Bachilo, S.M. and Nagarajaiah, S. and Weisman, R.B. (2012), "Strain paint: noncontact strain measurement using single-walled carbon nanotube composite coatings", *Nano Letters*, **12**(2), 3497-3500, DOI: 10.1021/nl301008m.

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