Geometrical and Chemical Dependent Hydrolysis Mechanisms of Silicon Nanomembranes for Biodegradable Electronics

Liu Wang[†♦], Yuan Gao[§♦], Fanqi Dai[†], Deying Kong[†], Huachun Wang[‡], Pengcheng Sun[†], Zhao Shi[‡], Xing Sheng[‡], Baoxing Xu*[§], Lan Yin*[†]

[†]School of Materials Science and Engineering, The Key Laboratory of Advanced Materials of Ministry of Education, State Key Laboratory of New Ceramics and Fine Processing, Tsinghua University, Beijing 100084, P. R. China (liuwang@mail.tsinghua.edu.cn; dfq15@mails.tsinghua.edu.cn; m18701391318@163.com; spch86@qq.com; lanyin@tsinghua.edu.cn)

[‡]Department of Electronic Engineering, Beijing National Research Center for Information Science and Technology, and Beijing Innovation Center for Future Chips, Tsinghua University, Beijing 100084, P. R. China (whc17@mails.tsinghua.edu.cn; shizhaohust@163.com; xingsheng@tsinghua.edu.cn)

[§]Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, Virginia 22904, United States (yg8ve@virginia.edu; bx4c@virginia.edu)

Abstract

Biodegradable electronic device that physically disappears in physiological or environmental solutions is emerging for potentially widespread applications in healthcare management and environmental sustainability [1-8]. Precise modulation of the lifetime with on-demand expectation to constituent materials, however, remains a key challenge. For silicon nanomembranes (Si NMs) that are the essential semiconductor component for high-performance biodegradable electronics at system level, in this work, we present a new mechanism of their hydrolysis behavior is presented (Figure 1) and a controlling strategy of Si NMs degradability by tuning surface charge density associated with dopant type and level is demonstrated. The experiments show a significant dependence of dissolution behavior on the surface charge status and dimensional size of Si NMs and mechanical stirring to solution environments. The presence of phosphates and potassium ions in solutions, lower dopant levels of p-type Si NMs or non-stirring environment will facilitate the degradation of Si NMs with higher dissolution rates and will also lead to a stronger size-dependent effect. Molecular dynamics (MD) simulations are conducted to reveal the ion adsorption mechanism of Si NMs with different surface charge densities and confirm the experimental observations. Tunable lifetime of the neural recording array based on Si NMs is achieved through geometry design. These results shed light on creation of new strategies to modulate the operational time frames of Si NMs and provide important baseline understanding for engineering high-performance biodegradable electronics.

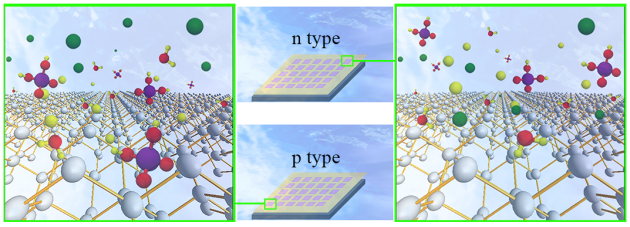

Figure 1. Chemical dependent hydrolysis mechanisms of silicon nanomembranes (p-type and n-type)

References

[1] Hwang, S.-W.; Tao, H.; Kim, D.-H.; Cheng, H.; Song, J.-K.; Rill, E.; Brenckle, M. A.; Panilaitis, B.; Won, S. M.; Kim, Y.-S.; Song, Y. M.; Yu, K. J.; Ameen, A.; Li, R.; Su, Y.; Yang, M.; Kaplan, D. L.; Zakin, M. R.; Slepian, M. J.; Huang, Y.; Omenetto, F. G.; Rogers, J. A., A Physically Transient Form of Silicon Electronics. Science, Vol. 337, No. 6102, pp. 1640-1644, 2012.

[2] Hwang, S. W.; Park, G.; Cheng, H.; Song, J. K.; Kang, S. K.; Yin, L.; Kim, J. H.; Omenetto, F. G.; Huang, Y.; Lee, K. M., 25th Anniversary Article: Materials for High-performance Biodegradable Semiconductor Devices. Advanced Materials, Vol. 26, No. 13, pp. 1992-2000, 2014.

[3] Kim, D.-H.; Kim, Y.-S.; Amsden, J.; Panilaitis, B.; Kaplan, D. L.; Omenetto, F. G.; Zakin, M. R.; Rogers, J. A., Silicon Electronics on Silk as a Path to Bioresorbable, Implantable Devices. Applied Physics Letters, Vol. 95, No. 13, pp. 133701, 2009.

[4] Irimia-Vladu, M., "Green" Electronics: Biodegradable and Biocompatible Materials and Devices for Sustainable Future. Chem. Soc. Rev. Vol. 43, No. 2, pp. 588-610, 2014.

[5] Hwang, S. W.; Huang, X.; Seo, J. H.; Song, J. K.; Kim, S.; Hage-Ali, S.; Chung, H. J.; Tao, H.; Omenetto, F. G.; Ma, Z., Materials for Bioresorbable Radio Frequency Electronics. Advanced Materials, Vol. 25, No. 26, pp. 3526-3531, 2013.

[6] Kang, S.-K.; Murphy, R. K.; Hwang, S.-W.; Lee, S. M.; Harburg, D. V.; Krueger, N. A.; Shin, J.; Gamble, P.; Cheng, H.; Yu, S., Bioresorbable Silicon Electronic Sensors for the Brain. Nature, Vol. 530, No. 7588, pp. 71-76, 2016.

[7] Yu, K. J.; Kuzum, D.; Hwang, S.-W.; Kim, B. H.; Juul, H.; Kim, N. H.; Won, S. M.; Chiang, K.; Trumpis, M.; Richardson, A. G., Bioresorbable Silicon Electronics for Transient Spatiotemporal Mapping of Electrical Activity from the Cerebral Cortex. Nature materials, Vol. 15, No. 7, pp. 782-791, 2016.

[8] Lu, L.; Yang, Z.; Meacham, K.; Cvetkovic, C.; Corbin, E. A.; Vázquez-Guardado, A.; Xue, M.; Yin, L.; Boroumand, J.; Pakeltis, G., Biodegradable Monocrystalline Silicon Photovoltaic Microcells as Power Supplies for Transient Biomedical Implants. Advanced Energy Materials, pp. 1703035, 2018.