doi:10.1017/S1431927620018772
Microsc. Microanal. 26 (Suppl 2), 2020
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Nanosized Field-effect Transistor Based on Germanium for Next Generation Biosensors in Scanning Ion-conductance Microscopy

Andrei Turutin[1], Aleksandr Temirov[1], Ilya Kubasov[1], Aleksandr Kislyuk[1], Mikhail Malinkovich[1], Yuriy Parkhomenko[1], Alexander Erofeev[2] and Yuri Korchev[3]

[1]National University of Science and Technology MISiS, Moscow, Moskva, Russia, [2]National University of Science and Technology ‘‘MISIS"; Lomonosov Moscow State University, Moscow, Moskva, Russia, [3]Imperial College London, London, England, United Kingdom

The new frontiers of the investigation into biosensors based on the field effect transistor (FET) opened the way for sensing single-molecular DNA [1], for single-cell analysis [2] and early cancer diagnosis [3]. Recently Zhang et al. [1] presented a FET based on poly-pyrrole (PPy). PPy-FET is manufactured on the tip of a spear-shaped dual carbon nanoelectrode derived from carbon deposition inside double-barrel nanopipettes. This structure can measure the pH gradient in three-dimensional space, detect adenosine triphosphate and identify biochemical properties of a single living cell. However, PPy is not stable and degrades after few measurement cycles. The challenge is to create the FET structure based on inorganic semiconductor materials on a nanometric tip which is biocompatible, does not degrade over time and is capable of detecting the gradient of a few mV potential in living cells, dendrites and axons of neurons *in vivo*.

We present the fabrication and study of the current–voltage (*I-V*) characteristic of a nano-FET based on germanium (Ge) which was deposited on the spearhead of a double-barrel quartz nanopipette with two carbon nanoelectrodes on the tip and along the surface of the nanopipette. The technology of creating and characterization of the double-barrel quartz nanopipette with two carbon nanoelectrodes can be found elsewhere [1,2]. The Ge was used due to the well-known technology, high electron mobility and carrier concentration at room temperature [4].

Germanium was deposited by RF magnetron sputtering on the spearhead of a double-barrel quartz nanopipette. The germanium layer was used as a channel of the nano-FET. The layer thickness was 50 nm. In the next step the Ge layer was covered by silicon oxide (approximately 5 nm) by using a second RF magnetron. The silicon oxide layer was used as an insulator and protected the Ge channel of the nano-FET. The schematic representation of the nano-FET on a nanopipette and the scanning electron microscopy (SEM) image provided by JSM-6700F microscope are shown in Figure 1. The germanium and the silicon oxide functional layers were magnetron-sputtered using a SUNPLA-40TM ADVAC-90PRO equipment. The nanopipette was placed in a home-made grounded box for *I-V* measurements. All the *I-V* measurements were carried out on a B1500A Semiconductor Device Parameter Analyzer.

A current–voltage (*I-V*) characteristic of the nano-FET is presented in Figure 2. The left panel of Figure 2 shows the dependence of the drain current on the drain-to-source voltage varying from -1 V to 1 V in steps of 50 mV. During the experiments we measured the *I-V* characteristic for more than 100 cycles (one cycle is a passage from negative to positive voltage and vice versa). This typical non-linear behavior of the *I-V* characteristic corresponds to a Schottky barrier structure.

In order to measure the FET *I-V* characteristic we prepared a third electrode (gate) by covering the nano-FET with a silver paste. The drain-to-source voltage varied from 0 V to 1 V in steps of 50 mV, and the gate voltage was changed from 0 V to 500 mV in steps of 10 mV. The results are presented in the right

https://doi.org/10.1017/S1431927620018772 Published online by Cambridge University Press

panel of Figure 2. The drain current drops from 190 nA at V_G=0 V to 60 nA at V_G=500 mV. The gate current was lower than 10 pA at V_{GS}=1 V. The nano-FET structure showed a sensitivity of 260 $nS \cdot V^{-1}$. This sensitivity is very competitive with recently presented results [5–8].

Furthermore, the suggested biosensor includes all the advantages of a double-barrel quartz nanopipette as intracellular measurements, extracellular analyte mapping, nanometric dimensions, and etc. It will be a multilateral biosensor platform to measure biopotentials of single living cells, dendrites and axons of neurons. The suggested nano-FET sensor is stable and demonstrates properties which are highly repeatable in time.

We acknowledge the financial support from the Ministry of Education and Science of the Russian Federation in the framework of the Increase Competitiveness Program of NUST ‘‘MISIS” implemented by a governmental decree dated 16 March 2013, No. 211 and the Russian Science Foundation supported production and characterization of nano-FET (grant no. 19-79-30062). The work was supported by the Ministry of Science and Higher Education of the Russian Federation as a part of the State Assignment in part of semiconductors nano films preparation (basic research, Project No. 0718-2020-0031 "New magnetoelectric composite materials based on oxide ferroelectrics having an ordered domain structure: production and properties").

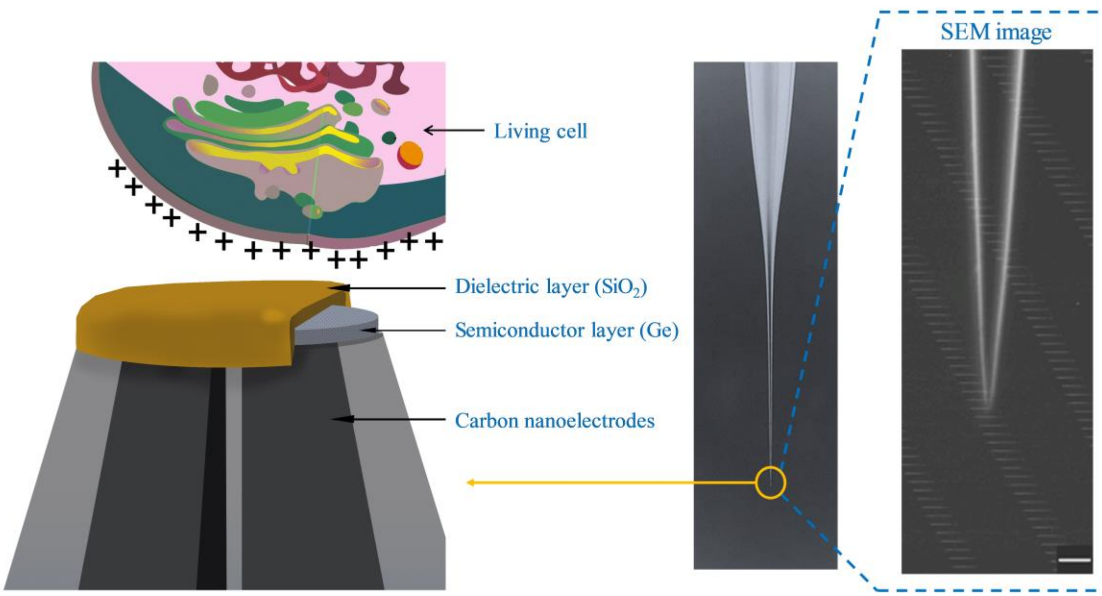

Figure 1. (left) Schematic representation of the nano-FET. (right) SEM image of the fabricated nano-FET double-barrel quartz nanopipette (scale bar 400 nm).

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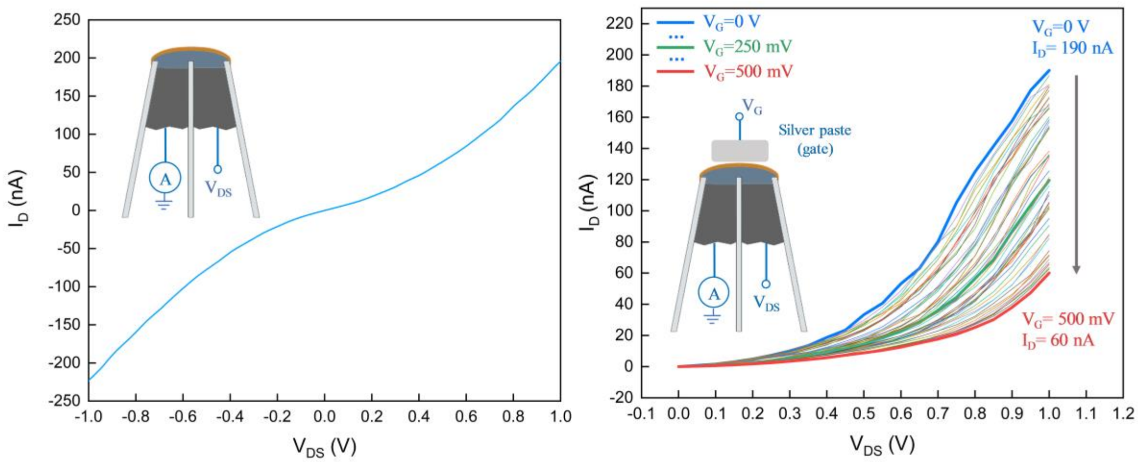

Figure 2. (left) I-V curve drain current vs VDS of the nano-FET. (right) I-V curves of the nano-FET vs gate voltage (VG).

References

1. Ren, R.; Zhang, Y.; Nadappuram, B. P.; Akpinar, B.; Klenerman, D.; Ivanov, A. P.; Edel, J. B.; Korchev, Y. Nanopore extended field-effect transistor for selective single-molecule biosensing. *Nat. Commun.* 2017, *8*, 586, doi:10.1038/s41467-017-00549-w.

2. Zhang, Y.; Clausmeyer, J.; Babakinejad, B.; López Córdoba, A.; Ali, T.; Shevchuk, A.; Takahashi, Y.; Novak, P.; Edwards, C.; Lab, M.; Gopal, S.; Chiappini, C.; Anand, U.; Magnani, L.; Coombes, R. C.; Gorelik, J.; Matsue, T.; Schuhmann, W.; Klenerman, D.; Sviderskaya, E. V.; Korchev, Y. Spearhead Nanometric Field-Effect Transistor Sensors for Single-Cell Analysis. *ACS Nano* 2016, *10*, 3214–3221, doi:10.1021/acsnano.5b05211.

3. Akhavan, O.; Ghaderi, E.; Rahighi, R.; Abdolahad, M. Spongy graphene electrode in electrochemical detection of leukemia at single-cell levels. *Carbon N. Y.* 2014, *79*, 654–663, doi:10.1016/j.carbon.2014.08.058.

4. Tsao, C.-Y.; Wong, J.; Huang, J.; Campbell, P.; Song, D.; Green, M. A. Structural dependence of electrical properties of Ge films prepared by RF magnetron sputtering. *Appl. Phys. A* 2011, *102*, 689–694, doi:10.1007/s00339-010-5957-9.

5. Duan, X.; Gao, R.; Xie, P.; Cohen-Karni, T.; Qing, Q.; Choe, H. S.; Tian, B.; Jiang, X.; Lieber, C. M. Intracellular recordings of action potentials by an extracellular nanoscale field-effect transistor. *Nat. Nanotechnol.* 2012, *7*, 174–179, doi:10.1038/nnano.2011.223.

6. Veigas, B.; Fortunato, E.; Baptista, P. Field Effect Sensors for Nucleic Acid Detection: Recent Advances and Future Perspectives. *Sensors* 2015, *15*, 10380–10398, doi:10.3390/s150510380.

7. Fu, T.-M.; Duan, X.; Jiang, Z.; Dai, X.; Xie, P.; Cheng, Z.; Lieber, C. M. Sub-10-nm intracellular bioelectronic probes from nanowire-nanotube heterostructures. *Proc. Natl. Acad. Sci.* 2014, *111*, 1259–1264, doi:10.1073/pnas.1323389111.

8. Li, Q.; Lu, N.; Wang, L.; Fan, C. Advances in Nanowire Transistor-Based Biosensors. *Small Methods* 2018, *2*, 1700263, doi:10.1002/smtd.201700263.

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