ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 19, No. 3. 2013

Application of Ge Nanowire for Two-Input Bistable Nanoelectromechanical Switch

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crossref http://dx.doi.org/10.5755/j01.ms.19.3.3086

Received 12 December 2012; accepted 13 February 2013

Recently, several research groups presented bistable two-terminal nanoelectromechanical switches based on individual single-clamped active element. All presented devices had one input electrode. Similar devices having two or more input electrodes have not been yet investigated. In this work we present the two-input bistable controlled nanoelectromechanical switch based on an individual single-clamped Ge nanowire. The switch is realised using *in-situ* SEM technique and operating due to balancing of electrostatic, adhesion and elastic forces. The operation conditions of the device are investigated and presented. The advantages and drawbacks of the device are discussed.
Keywords: nanowire, bistable switch, semicondutor, NEMS.

1. INTRODUCTION

Nanoelectromechanical (NEM) devices present interesting and unique characteristics by exploiting nanoscale effects, which differ greatly from their predecessor microelectromechanical systems (MEMSs)[1]. The power consumption and heat capacity of a NEM device is expected to be extremely low. During the past few years, carbon nanotubes were used as promising active components in NEM devices [1 – 6]. However, other materials such as metallic and semiconductor nanowires [7 – 9] have also been integrated in NEMS as active elements. Single crystalline nanowires are excellent candidates for NEM devices due to their uniform chemical and physical structure, low mass, and good structural and compositional reproducibility.

Typical NEMS examples are nanorelays and switches (ON-OFF devices), [2 – 4, 7, 8, 10 – 15] which are the point of interest of this paper.

As far as most ON-OFF devices operate as three-terminal devices, using three electrodes: source, drain and gate electrode, which induces a charge in the active element, [2, 3, 14, 15] two-terminal bistable ON-OFF devices have also been investigated both theoretically [16, 17] and experimentally [3, 4, 7 – 10, 14, 15, 18, 19]. The basic operating principle underlying bistable NEM switches is the interplay of electrostatic energy, adhesion energy and elastic energy. The electrostatic force pulls in the active element (nanowire or nanotube) to make contact with the electrode (ON position). The elastic forces assotiated with device operation are comparable with the adhesive forces (that hold these devices together) and detaches the active element from the electrode (OFF position). The advantage of the two-terminal NEMS in comparison to the three-terminal NEMS is their simple configuration in which only two electrodes are used. Distances between the electrodes can be adjusted during the experiment using *in-situ* transmission electron microscope (TEM) [20, 21] or scanning electron microscope (SEM) techniques which is not possible in case of three-terminal NEM devices due to their configuration mostly acieved using lithography methods.

An investigation of the operational conditions of bistable ON-OFF NEMS having two possible input electrodes has not yet been demonstrated. In this paper we present an *in-situ* scanning electrone microscope (SEM) investigation of the bistable nanoelectromechanical device using an individual single clamped Ge nanowire as an active element and proving two possible input positions are attainable.

2. EXPERIMENTAL SETUP

The Ge nanowires used as active elements are grown using the supercritical fluid method and are single crystalline in nature but covered with natural amorphous oxide layer [7]. The lenghts of the nanowires used in experiments were in the range of 5 μm – 30 μm and the radii were in the range of 25 nm – 150 nm. The system of 13D SmarAct nanopositioners inside Hitachi FE-4800 scanning electron microscope is used for process visualization and nanowire – electrode distances adjustment. Such type of system is very flexible and allows adjusting electrode and nanowire positions without preparation of new specimens. The Ge nanowires are glued onto the electrochemically etched gold tip (sample tip) by electroconductive epoxy. This method of clamping the nanowires provides large contact area to the electrode in comparison with the contact area that established between the free end of the nanowire and the input electrode during device operation. We use Keithley-6430 for characteristic measurements.

The schematic of the experiment setup is shown at the Fig. 1. Any of input electrodes i1 and i2 can be selected

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using the active element of NEMS – semiconductive Ge nanowire – and the selected signal can be forwarded to the signal line S and registered.

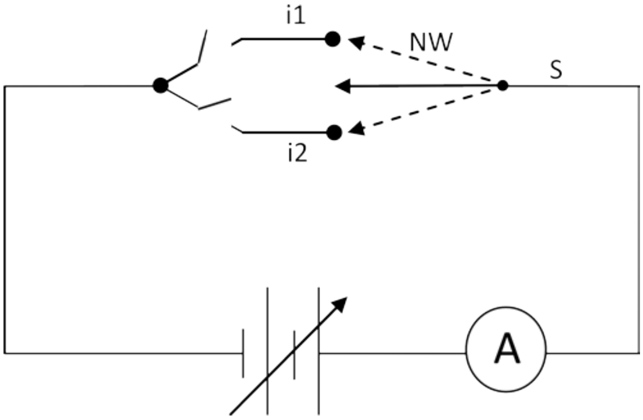

Fig. 1. The schematics of the two-input NEMS. The active element – nanowire - can be connected to any of inputs (i1 or i2) and the signal can be transferred then to the signal line S

3. RESULTS AND DISCUSSION

When designing the ON-OFF switch based on an individual single clamped nanowire, the initial distance between the free end of the nanowire and the input electrode should be large enough to avoid the nanowire „sticking" in the ON (contact) position. The „sticking" is determined mainly by adhesion between the end of the active element and the electrode that is overcoming the elastic forces of the bended nanowire.

Fig. 2, a – d, illustrates the configuration and operation of the device. At the start the active element – Ge nanowire (length is 18 µm and radius is around 100 nm) – is located in a neutral position between the two input electrodes (Fig. 2, a). The initial distance between the nanowire end and each of two input electrodes is 3 µm. When the voltage sweep is applied between one of the electrodes and sample tip, the nanowire bends towards the input electrode due to the electrostatic force and comes to the "jump-to-contact" position, where the repulsive force (elastic force of the bended nanowire) equals to the attractive force being the sum of the electrostatic and van der Waals forces (Fig. 3). After that point the electrostatic attractive force overcomes the elastic force of the bended nanowire and the nanowire connects to the input electrode. The "jump-to-contact" was observed at voltage of 22 V from the distance of 40 nm (Fig. 2, b).

To calculate the electrostatic attractive force between the nanowire and the input electrode, the sphere-plane geometry, commonly used in AFM studies [22], is used as it has being shown that such a model fits well to the experimental data for nanowire-electrode interaction. Using this model, the electrostatic force can be calculated as

$$F_{el} = \frac{\pi \varepsilon \varepsilon_0 R U^2}{d}, \tag{1}$$

where R is the nanowire's radius, U is the voltage applied between the input electrode and the nanowire and d is the distance between the end of the nanowire and the input electrode.

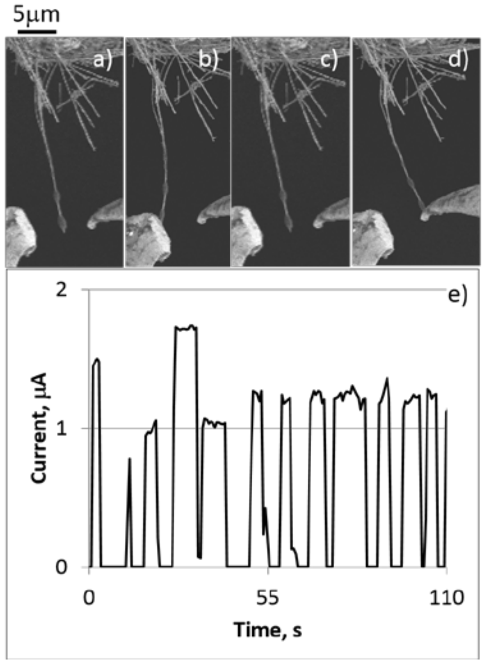

Fig. 2. The two-input NEMS operating due to the elastic force of the nanowire. a + c – neutral position of the active element – Ge nanowire; b + d – the active element in contact with input electrodes; e – current-time curve demonstrating the NEMS operation

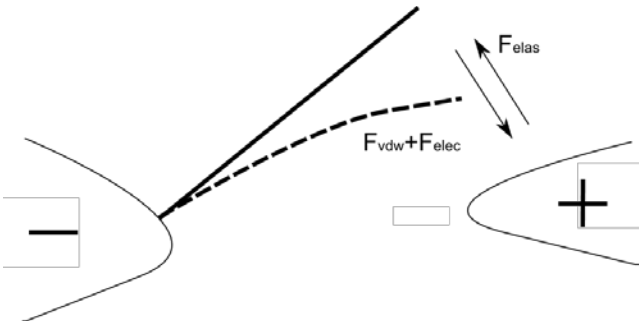

Fig. 3. The schematics of the jump-to-contact position of the nanowire. After the voltage is applied between the electrodes, the nanowire moves from the neutral position (solid line) to the jump-to-contact position (dashed line). In the jump-to-contact position the repulsive elastic force of the nanowire F_{elas} equals to the sum of the attractive forces (van der Waals force F_{vdw} and electrostatic force F_{elec})

The electrostatic force of the nanowire at the „jump-to-contact" moment calculated by (1) is $5.4 \cdot 10^{-7}$ N, which means that in the contact position the elastic force of the bended nanowire is not less then $5.4 \cdot 10^{-7}$ N.

The Van der Waals force between the nanowire end and the electrode can be calculated using the model for sphere-plane van der Waals interaction [23]:

$$F_{vdw} = \frac{Ad}{12 z_0^2}, \tag{2}$$

where A is the Hamaker constant for Au-Ge combination (A = 2.5 eV [23]), d is the nanowire's diameter and z_0 is the separation distance. The Van der Waals force for the "jump-to-contact" position of the nanowire calculated by (2) equals to $5 \cdot 10^{-13}$ N which is 6 orders of magnitude weaker then the electrostatic force, therefore at this stage the Van der Waals force can be ignored.

The adhesion force at the Ge-Au nanocontact area is calculated using the generalised transition equation developed by Carpick et al [24], which is an excellent approximation to the Maugis-Dugdale model [25, 26]. Experimental verification of Maugis theory for nanocontacts ir reported in [21, 24]. The value of the adhesion force can be found by siltumaneously solving next equations:

$$\frac{a}{a_{0(\alpha)}} = \left(\frac{\alpha + \sqrt{1 - \frac{F}{F_{c(\alpha)}}}}{1+\alpha} \right)^{2/3} , \quad (3)$$

where a is the contact radius, a_0 is the contact radus at zero load, F is the load, F_c is the critical negative load and α is the transition parameter and should be in range $0 < \alpha < 1$. The transition parameter can be calculated using the following equation:

$$\lambda = -0.924 \ln(1 - 1.02\alpha) , \quad (4)$$

where λ is the parameter, defined by Maugis [25], and equals to

$$\lambda = 2\sigma_0 \left(\frac{R}{\pi\gamma K^2} \right)^{1/3} , \quad (5)$$

where σ_0 is the contact adhesive stress (force per unit area) between two surfaces, R is the curvature radius of the end of the nanowire, γ is the work of adhesion and the K is the combined elastic modulus of the nanowire and the electrode. The K can be calculated as

$$K = \frac{4}{3} \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \right)^{-1} , \quad (6)$$

where E_1 and E_2 are elastic moduli of nanowire (Ge) and electrode (Au) materials (112 GPa [27] and 117 GPa [21] respectively) and ν_1 and ν_2 are Poisson's ratios assotiated with each body (0.44 for gold and 0.28 for germanium [28]). The contact radius at zero load a_0 and the critical negative load F_c can be represented in Maugis' nondimensional units

$$F_c^{'}(\lambda) = \frac{F_c}{\pi\gamma R} \quad (7)$$

and

$$a_0^{'}(\lambda) = a_0 \left(\frac{K}{\pi\gamma R^2} \right)^{1/3} \quad (8)$$

and easily calculated by empirical equations determined by Carpick et al [27]:

$$a_0^{'} = 1.54 + 0.279 \left(\frac{2.28\lambda^{1.3} - 1}{2.28\lambda^{1.3} + 1} \right); \quad (9)$$

$$F_c^{'}(\lambda) = -\frac{7}{4} + \frac{1}{4} \left(\frac{4.04\lambda^{1.4} - 1}{4.04\lambda^{1.4} + 1} \right). \quad (10)$$

The adhesion force for the nanowire-electrode contact calculated using equations (3 – 10) is $3.90 \cdot 10^{-7}$ N. Therefore, the elastic force of the bended nanowire (estimated as $\geq 5.40 \cdot 10^{-7}$ N) is strong enough to detach the nanowire from the electrode when the electrostatic field is switched off. When the electrostatic field is turned off, the elastic force of the nanowire pulls it out of contact and the nanowire returns to the neutral position (Fig. 2, c). After that the cycle can be repeated with the other input electrode (Fig. 2, d). To achieve the stable work of the device, the operating voltage should be taken 10 V – 15 V higher then "jump-to-contact" voltage. The higher operating voltage is required to compensate unwanted fluctuations in the system configuration. Our experience shows that if "jump-to-contact" voltages are in the range of 20 V – 30 V, then the optimal operating voltage should be in the range of 40 V – 45 V. Stability of the switches during multiple switching events is demonstrated in Figure 2, e. The current jumps up to 2 µA are registered every time when the nanowire is connected to the electrode.

Neither melting nor destruction of the nanowire were observed during multiple switching of the device. When the voltage is switched from the electrode, which is in contact with the active element (the nanowire), to the second input electrode, the active element is immediately detached from the contact by elastic force and moves towards the input electrode through the neutral position under influence of the electrostatic force. It has been estimated that the electrostatic force does not play noticable role in the nanowire detachment due to it's weakness at large distances. The calculated electrostatic force at the interelectrode distance of 6 µm and voltage 40 V is around $1.5 \cdot 10^{-8}$ N, which is 26 times weaker then the adhesion force at the nanowire-electrode contact area.

4. CONCLUSIONS

The work we presented here shows the method of the realization of two-input bistable controlled ON-OFF switch based on the individual free standing Ge nanowire. The device`s operation is based on the nanowire detachment from the electrode by the elastic force of the bended nanowire. The device shows the stable switching between the two input electrodes at the operating voltage 40 V – 45 V and initial distances between the input electrodes 6 µm. We observed no any damage or degradation of the active element during the experiment. We presume that similar devices having more than two input electrodes can be realized in the same way. Disadvantage of the device in this configuration is that the electrode-nanowire distances have to be adjusted for every individual nanowire. Further study in this area of interest should be pursued. In particular addressing (1) numerical modelling of the electrical and mechanical contact between the nanowire and (2) the electrode and the universal method of the detachment of the nanowire from the contact, which will be less dependent on the system's configuration and elastic properties of the individual nanowire.

Acknowledgements

This work has been supported by Latvia Council of Science. J. A. and R. M. acknowledge the European Social

Fund within the project «Support for Doctoral Studies at University of Latvia» for finacial support.

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