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Citation: Appl. Phys. Lett. **102**, 043701 (2013); doi: 10.1063/1.4789904
View online: http://dx.doi.org/10.1063/1.4789904
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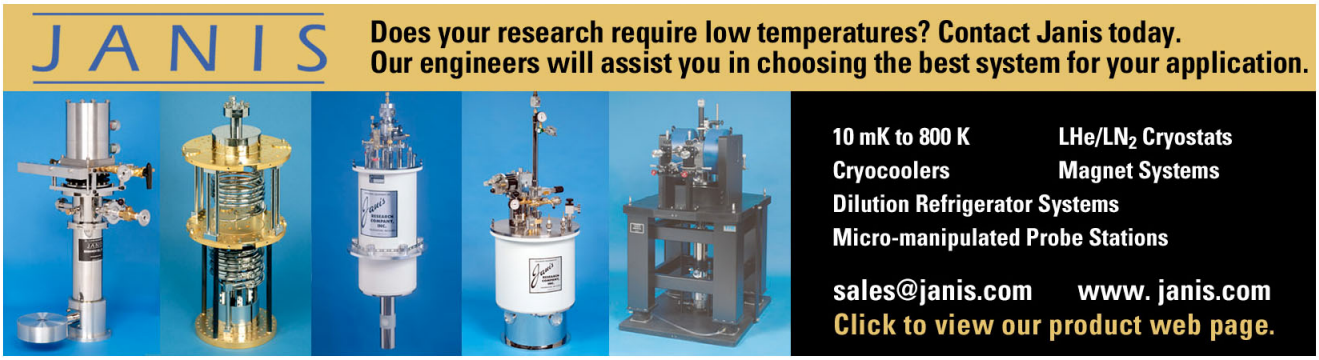

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A biristor based on a floating-body silicon nanowire for biosensor applications

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(Received 16 September 2012; accepted 16 January 2013; published online 29 January 2013)

A silicon nanowire (SiNW), which has been named "biristor" (bistable resistor), is demonstrated for biosensor applications. The SiNW is composed of three segments: n-type (source), p-type (floating-body), and n-type (drain). Its structure is based on a metal-oxide-semiconductor field-effect transistor without a gate. The biristor uses the uncovered floating-body as a sensing site, and it is triggered by impact ionization. A charge effect arising from biomolecules influences the triggering voltage, which is a sensing metric and changes the resistance of the SiNW. The biristor can be a promising candidate for biosensors in terms of complementary metal-oxide-semiconductor compatibility, low-cost, and compact density. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4789904]

Semiconducting nanowires (NWs) have attracted a great deal of attention from researchers as a powerful approach for point-of-care testing (POCT) system due to their ability to detect biomolecules directly and electrically with high sensitivity.[1,2] An underlying detection principle using semiconducting NW is based on the gating effect of biomolecules immobilized on surface of the NW. As the applied gate voltage modulates the channel current in field-effect transistors, charged biomolecules on the NW surface affect the channel potential and accordingly change the channel current. Silicon nanowire (SiNW)-based sensors have been proposed several times for detection of DNA,[3,4] cancer markers,[5,6] and virus antibodies;[7,8] however, the sensing metric has only been the change of conductivity, i.e., current change.

On the other hand, a SiNW composed of an n^+, p, and n^+ doped region, which is known as a "*biristor*," was reported by our group for use in memory devices.[9] It was built on a silicon-on-insulator (SOI) substrate. The name biristor arises from the words bistable resistor; this device was enabled by impact ionization.

In this Letter, a biristor built on a bulk silicon substrate is proposed for use as a biosensor. The doping profile of the biristor is the same as that of a metal-oxide-semiconductor field-effect transistor (MOSFET) except the gate; the doped regions correspond to the source, body, and drain. The body, which serves as a sensing site, is left floating; thus, the proposed biristor needs just two terminals because it does not have the gate. However, biomolecules that are attached on the floating-body act as a virtual gate. An important point to notice here is that the detection principle does not rely on a simple conductance change but on the impact ionization phenomenon, which iteratively amplifies a signal stemming from biomolecules. As a proof-of-the concept, negatively and positively charged polymers are detected. Thereafter, antibodies of avian influenza (AI) are detected without any use of labeling steps for practical applications.

The concept of the proposed biosensor is shown in Fig. 1. The floating-body SiNW, i.e., the biristor, has two resistance states. It initially stays at a high resistance state (HRS) under a low voltage regime. However, it abruptly switches to a low resistance state (LRS) via impact ionization under a high voltage regime. As the voltage increases at the drain, impact ionization is triggered, and this generates excess holes in the floating-body. As a result, the potential barrier between the body and the source is lowered. Consequently, the current flowing through the body is amplified by an iterative carrier generation, i.e., a positive feedback mechanism. The device governed by the positive feedback mechanism can be sensitive to external perturbations; however, the

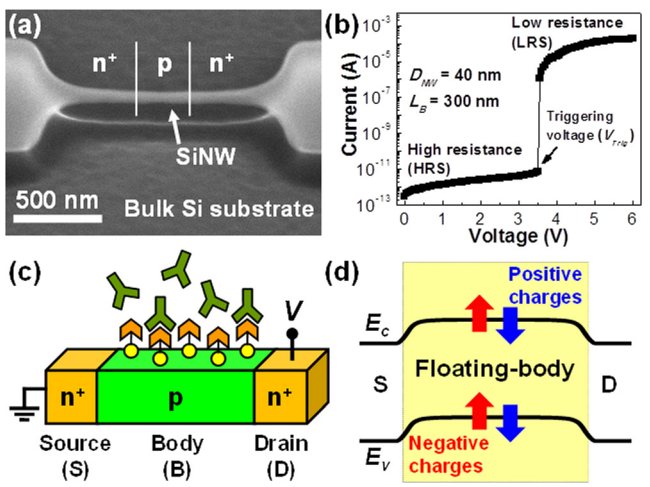

FIG. 1. (a) Tilted image of the fabricated biristor taken from a scanning electron microscope (SEM). (b) Measured *I-V* characteristics of the biristor. The electrical state abruptly transited from a high resistance state to a low resistance state via impact ionization. (c) Schematic of the proposed biosensor with immobilized biomolecules on the surface of the SiNW. (d) Energy band diagram of the biristor. The charged biomolecules on the SiNW alter the potential of the floating-body according to the charge polarity.

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biristor is tolerable against such noise. Reliable current-voltage behavior was confirmed by iterative measurements (data not shown). Also, the accumulated holes in the floating-body after measurement are recombined; thus, the potential of the floating-body returns to its initial state within 1 sec.[9] Consequently, the previous bias history will not influence the next measurement. The proposed biristor has a floating-body for a sensing region; its electric characteristics are determined by the potential of the body. As charged biomolecules are introduced on the surface of the SiNW, the current-voltage (*I-V*) curves can be varied due to the modulation of the body potential. In the proposed biristor, the triggering voltage (V_{Trig}) is defined when HRS abruptly changes to LRS by the iterative impact ionization in a plot of *I-V*. This V_{Trig} can be analogous to the threshold voltage to discern on- or off-state in a MOSFET. When target biomolecules are introduced on the biristor, V_{Trig} is accordingly changed; thus, the target biomolecules can be detected by tracing the change of V_{Trig}. The charged biomolecules on the biristor influence the body potential and trigger impact ionization iteratively; thus, a signal stemming from them can be continuously amplified. It is also noteworthy that the current ratio between at HRS and LRS is larger than 10^6, which is always clearly distinctive. These features can confirm the idea that the biristor, which was heterogeneously doped across the SiNW, i.e., n^+-p-n^+, can be superior to a conventional SiNW-based biosensor that was homogeneously doped across the SiNW.

The proposed biristor was fabricated by use of complementary metal-oxide-semiconductor (CMOS) technology; the process flow is shown in Fig. 2. First, a surface of a bulk silicon (Si) was doped by boron (B) with an implant dose of $10^{13}\,cm^{-2}$ to make a p-type body region. The bulk substrate was patterned by anisotropic etching to create the SiNW with a width (W_{NW}) of 40 nm; then, the bottom part of the SiNW was completely etched out by isotropic etching to separate the SiNW from the bulk substrate, i.e., via a one-step etching route.[10] Next, the bottom part of the suspended SiNW was partially filled with a silicon dioxide (SiO_2) for device isolation. After the body region was covered with a photoresist (PR), arsenic (As) with a dose of $5 \times 10^{15}\,cm^{-2}$ was implanted to make a heavily doped n-type source and drain. The dopants were activated using an RTA process at 1000 °C for 10 sec. Consequently, the floating-body SiNW that has an n^+-p-n^+ doping profile with a body length (L_B) of 300 nm was fabricated on a bulk Si substrate. Finally, SiO_2 with a thickness of 3 nm was thermally grown for stable immobilization of biomolecules on the SiNW surface. It should be noted that the biristor is realized on the bulk Si substrate by top-down approaches. Thus, this process is very attractive for low cost and high density sensor array by virtue of mature semiconductor fabrication technology and perfect process compatibility.

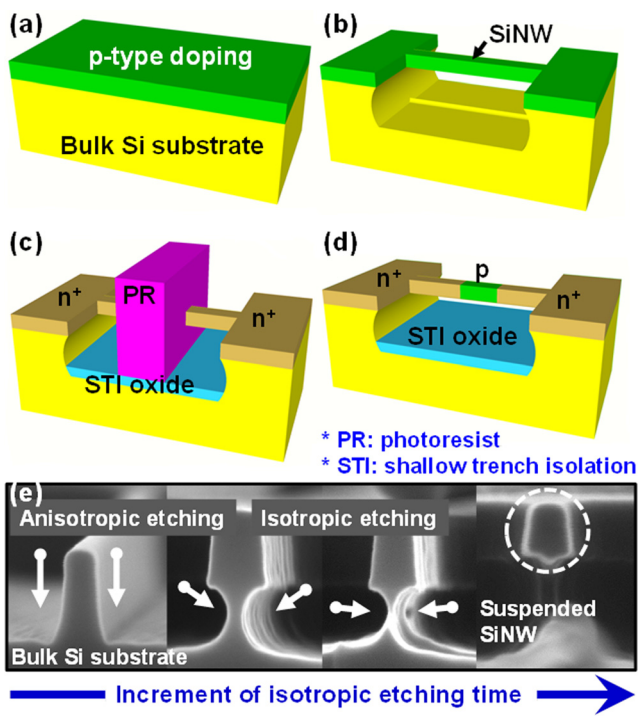

FIG. 2. Flow of fabrication process from (a) to (d) for the biristor, and (e) cross-sectional SEM images of the SiNW with different isotropic etching times. The suspended SiNW on a bulk Si substrate is fabricated by the one-step etching route known as the Bosch process. For the formation of the n^+-p-n^+ junctions, the center of the p-type SiNW is passivated by PR during the implantation of n-type dopants.

Two different well-known charged polymers were deposited to prove the working principle of the biristor. Polyelectrolytes of poly(sodium 4-styrene sulfonate) (PSS) and poly(allylamine hydrochloride) (PAH) (Sigma-Aldrich), which are negatively and positively charged, respectively, were used to intentionally introduce external charges onto the SiNW surface.[11] The biristor was first silanized with (3-aminopropyl)triethoxysilane (APTES) by immersing the device in a 1% APTES ethanol solution for 30 min. After immersion, the device was washed with ethanol and heated at 120 °C for 20 min. Subsequently, the APTES-modified device was immersed into 50 mM PSS solution diluted with deionized water for 1 hr to deposit PSS molecules on the SiNW surface. Afterwards, the device was washed with deionized water and dried with nitrogen gas. Next, PAH was introduced to the PSS-deposited device in the same way. The electrical characteristics of the biristor are shown in Fig. 3. Different V_{Trig} was observed according to the charge polarity of the attached polymers. When PSS was introduced onto the surface of the SiNW, the potential of the floating-body decreased, i.e., the negative charges act as higher body doping than the initial state. Accordingly, V_{Trig} increased. However, V_{Trig} decreased again by PAH due to the partial compensation of negative charges. It is worthwhile to note that the change of the body potential due to the charged molecules leads to a significant change of V_{Trig} because the impact ionization is very sensitive to the body potential. These results indicate that the biristor can electrically detect charged biomolecules via monitoring the change of V_{Trig}.

To verify the concept of the biristor as a practical biosensor, the specific antigen-antibody interaction was utilized for the bio-experiments. In this work, an antibody of avian influenza virus (anti-AI) was detected by use of the AI antigen (AIa) functionalized on the surface of the nanowire. The AIa can be immobilized through the silica-binding protein (SBP) that strongly binds to the SiO_2 surface.[12] That is, AIa fused with SBP (SBP-AIa) was used and it resulted in the

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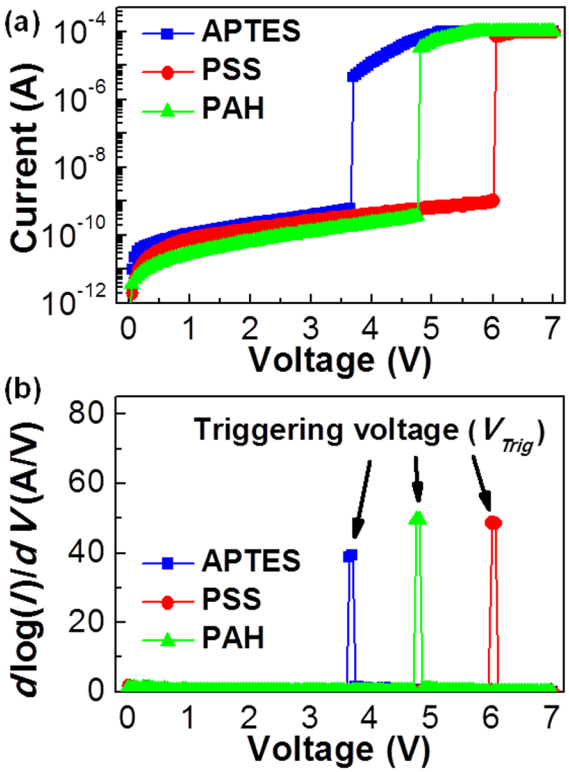

FIG. 3. (a) Effects of charge on V_{Trig} shift. The electrical characteristics of the biristor are significantly changed by both negative and positive charged polymers. (b) Each peak point, which is accurately obtained from the derivative of I with respect to V, is defined as V_{Trig}.

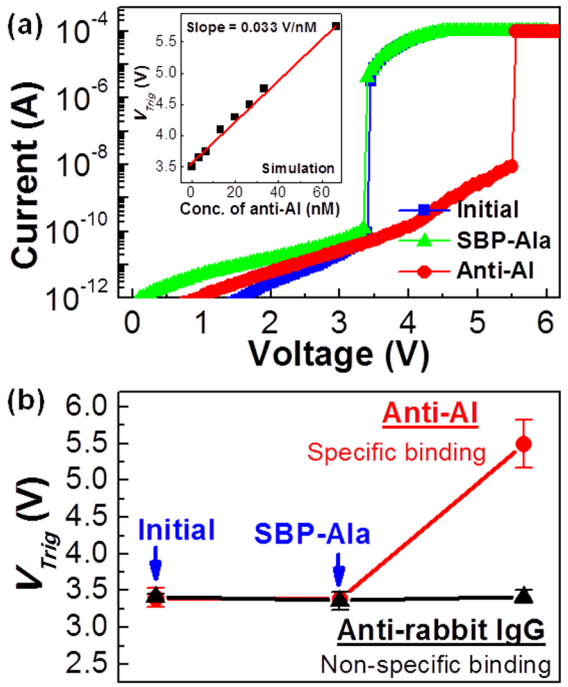

FIG. 4. (a) Measured I-V characteristics of the biristor with bio-experiments. SBP-AIa with 25 μg/ml (86.7 nM) is first immobilized; then, anti-AI at 10 μg/ml (66.8 nM) is specifically bound with AIa. After anti-AI binding, V_{Trig} increases from 3.5 V to 5.5 V due to the negative charge polarity. The slope in the inset stands for the detection sensitivity of the proposed device. (b) Summarized experimental results of specific and non-specific bindings. The concentration of anti-rabbit IgG is also 10 μg/ml (66.8 nM). Notable shift of V_{Trig} is only observed in the case of a specific antigen-antibody reaction. The error bar is the standard deviation of 12 devices.

efficient immobilization of the AIa molecule on the SiO_2 surface without any surface modification. The SBP-AIa dissolved in 25 μg/ml (86.7 nM) of phosphate-buffered saline (PBS, pH 7.4) solution was cast on the biristor for 1 hr at room temperature. Then, the device was rinsed several times with deionized water and was subsequently dried with nitrogen gas. Anti-AI dissolved in 10 μg/ml (66.8 nM) of PBS solution was introduced on the SBP-AIa-functionalized device in the same manner. Consequently, specific binding between SBP-AIa and anti-AI occurred. Figure 4 shows the I-V characteristics before and after anti-AI binding in the same device and the statistical distribution of V_{Trig} according to each of the bio-experimental steps. The data set for each experimental step were extracted from 12 devices. There is a large shift of V_{Trig} after the binding of the negatively charged anti-AI. The detection sensitivity of 0.033 V/nM was obtained from numerical simulations based on the experimental results, as plotted in the inset of Fig. 4(a). As a control bio-experiment, non-specific binding by use of anti-rabbit immunoglobulin (IgG) that is whole IgG antibodies extracted from a rabbit was carried out for a false positive test. No significant change of V_{Trig} due to the non-specific binding between SBP-AIa and anti-rabbit IgG was observed. Anti-rabbit IgG and anti-AI have the same basic structure, but they show different antigen-binding sites. That is, the biristor can selectively detect anti-AI while the non-specific binding with the anti-rabbit IgG is neglected because the AI antigen immobilized on the device surface through SBP-AIa allows anti-AI to be specifically bound. Therefore, it is concluded that the large change of V_{Trig} stems from the charged biomolecules and that the proposed biristor selectively detects targeted biomolecules without a labeling process.

In summary, a biristor based on a floating-body SiNW was proposed for the label-free electrical detection of biomolecules. The electrical characteristics of the proposed biosensor were effectively modulated by negatively charged PSS and positively charged PAH. When SBP-AIa and anti-AI were bounded on the body region of the biristor, the triggering voltage (V_{Trig}) was significantly changed by the negative charges of anti-AI. The large change of V_{Trig} was found to originate from the iterative impact ionization. With the merits of a fully CMOS-compatible process and a simple device structure, the proposed biristor can be a promising candidate for use as a chip-based biosensor.

This work was supported by the National Research and Development Program (NRDP, 2012-0001131) for the development of biomedical function monitoring biosensors and by the Center for Integrated Smart Sensors funded by the Ministry of Education, Science and Technology as Global Frontier Project (CISS-2012M3A6A6054187).

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