Fabrication and characterization of a nanoelectromechanical switch with 15-nm-thick suspension air gap

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We developed titanium nitride (TiN) based nanoelectromechanical (NEM) switch with the smallest suspension air-gap thickness ever made to date by a "top-down" complementary metal-oxide semiconductor fabrication methods. Cantilever-type NEM switch with a 15-nm-thick suspension air gap and a 35-nm-thick TiN beam was successfully fabricated and characterized. The fabricated cantilever-type NEM switch showed an essentially zero off current, an abrupt switching with less than 3 mV/decade, and an on/off current ratio exceeding 10^5 in air ambient. Also achieved was an endurance of over several hundreds of switching cycles under dc and ac biases in air ambient. [DOI: 10.1063/1.2892659]

Aggressive scaling of complementary metal-oxide semiconductor (CMOS) devices has provided a significant stimulus for advances in the semiconductor industry over the past four decades. However, many difficult challenges in continuing to scale down beyond sub-100-nm have been encountered so far, such as power dissipation, parasitic leakage currents, and short-channel effects.[1,2] Several devices based on microelectromechanical[3–5] (MEM) and nanoelectromechanical[6–11] (NEM) switches have been recently proposed as one of the promising solutions, since they show excellent on/off current characteristics due to an essentially zero off current and an abrupt switching. Also, they have robustness under harsh environments such as radiation and low/high temperature.

MEM systems (MEMS) have already had a noteworthy impact on rf circuits, automotive, aerospace, and information technology areas.[12] NEM systems (NEMS) are a thousand times smaller than MEMS and have the potential to enable revolutionary advances for future applications.[12–16] Extensive studies have been carried out on NEMS applications of suspended carbon nanotubes (CNTs) due to their superior electrical and mechanical properties.[17–20] The CNT-based NEM devices with low power consumption and operating frequencies in the gigahertz range make them attractive for switch, memory, and sensor applications. However, existing devices based on the CNTs grown using a "bottom-up" approach are still far from realization due to many obstacles such as difficulty in controlling the position and population of each CNTs.

In this letter, the cantilever-type NEM switch with a 15-nm-thick suspension air gap and a 35-nm-thick titanium nitride (TiN) beam was fabricated by a conventional complementary metal-oxide semiconductor (CMOS) process to show the possibility of a "top-down" approach for the fabrication of NEM switches rather than a widely used bottom-up approach so far. The fabricated NEM switch successfully demonstrated excellent on/off current characteristics and repetitive switching operation under dc and ac biases in air ambient.

Schematic diagram of the cantilever-type NEM switch is shown in Fig. 1(a). The cantilever-type NEM switch consists of a bottom electrode that is separated and isolated from the adjacent electrodes by a shallow trench isolation (STI) oxide, as well as a suspended beam hanging over the bottom electrode that is anchored on the STI oxide. When the voltage is applied between the suspended beam and the bottom electrode, the induced electrostatic force pulls the suspended beam down toward the bottom electrode, eventually bringing it into contact with the bottom electrode when the voltage exceeds a certain minimum known as the pull-in voltage. Consequently, an electric current can flow between the suspended beam and the bottom electrode.

Figure 1(b) shows scanning electron microscope (SEM) photograph of the fabricated cantilever-type NEM switch. Here, thermally grown silicon dioxide (SiO_2), tungsten (W), TiN, and sacrificial poly-Si were sequentially deposited on a bulk Si substrate to form the bottom electrode. The sacrificial poly-Si was deposited by a thin poly-Si deposition method that entails deposition and etch-back process to obtain an ultrathin suspension air gap. The bottom electrode was patterned and isolated using the conventional STI method, employing a STI trench etch, a STI oxide gap fill, and a STI oxide chemical-mechanical polishing process. TiN was selected as the suspended beam material owing to its unique properties such as a low electrical resistivity of 20 $\mu\Omega$ cm, a high Young's modulus of 600 GPa, and an excellent chemical inertness to form the suspended beam.[21] After an annealing process for relaxing the residual stress of the TiN film, the sacrificial poly-Si was selectively removed by an isotropic wet etching with high selectivity to TiN and SiO_2, and a critical point drying process was finally conducted in order to prevent release-related stiction.

Figure 2(a) shows SEM photograph of the disappeared beam by localized contact melting, which has no initial oxide layer in the contact area, whereas Fig. 2(b) shows the successfully fabricated and flat cantilever-type NEM switch by

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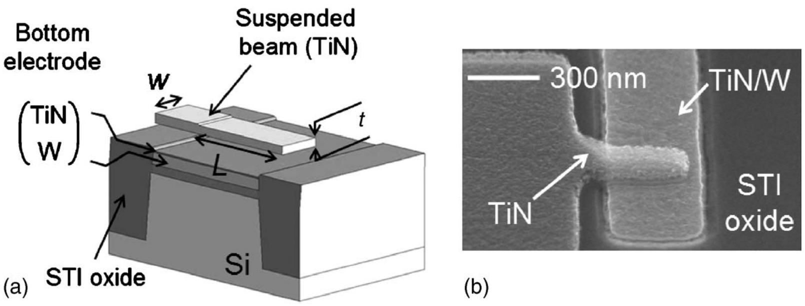

FIG. 1. (a) Schematic diagram of the cantilever-type NEM switch composed of the suspended beam and the bottom electrode. (b) SEM photograph of the cantilever-type NEM switch fabricated by using conventional top-down CMOS fabrication technology.

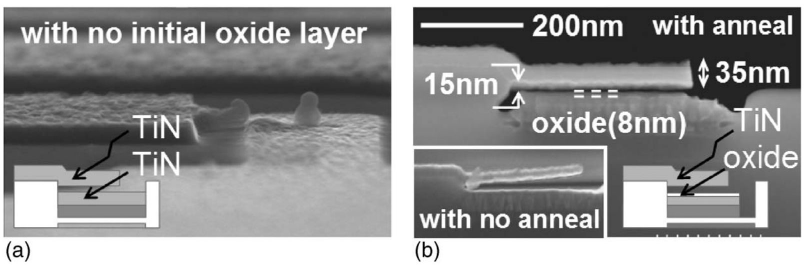

FIG. 2. SEM photographs of (a) the disappeared beam by the localized contact melting, which has no initial oxide layer and (b) the successfully fabricated and flat cantilever-type NEM switch by employing an ultrathin oxide layer and an annealing process. The inset shows the suspended beam fabricated with initial oxide layer and no annealing process.

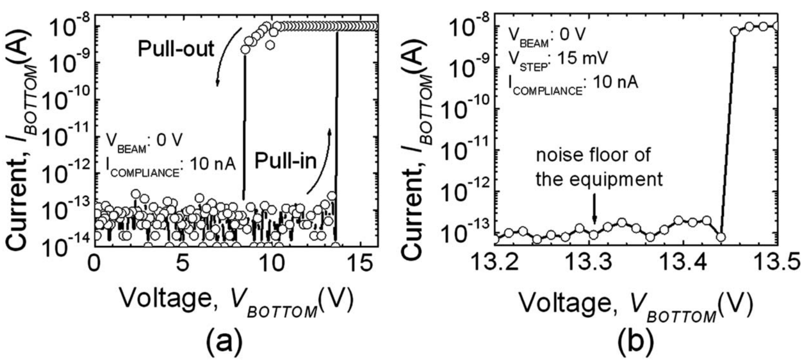

FIG. 3. (a) *I-V* hysteresis curve of the fabricated cantilever-type NEM switch ($w/L/t$ =200 nm/300 nm/35 nm). (b) Magnified view of the pull-in region, showing ideal on/off current characteristics.

employing an ultrathin oxide layer having a thickness of 8 nm, which was deposited on the TiN bottom electrode, and an annealing process. The suspended beam of the fabricated NEM switch with TiN-to-TiN contact was melted down after the one-time switching. The main reason for this is expected to be an electrical arcing or excessive Joule heating, which occurred at a localized region of the tip of the suspended beam due to the high current density and high pull-in voltage. In order to avoid the contact problems related to the electrical arcing and Joule heating in the NEM switches with direct metal-to-metal contact, the ultrathin insulating layer was placed on the bottom electrode, as shown in Fig. 2(b). The actual thickness of the suspension air gap and the suspended beam of the fabricated cantilever-type NEM switch were measured to be a 15 and 35 nm, respectively. The annealing process, which was done before the beam release, successfully eliminated any stress-related deformation of the suspended TiN beam, which might cause an increase of the pull-in voltage because of the enlarged air gap, as shown in the inset of Fig. 2(b).

Figures 3(a) and 3(b) show *I-V* plots of the fabricated cantilever-type NEM switch ($w/L/t$ =200 nm/300 nm/35 nm) with the oxide insulating layer. The fabricated NEM switch has a counterclockwise hysteresis curve with a pull-in voltage of about 13 V and a pull-out voltage of about 8 V, as shown in Fig. 3(a). A compliance current of 10 nA was still used to avoid the localized excessive Joule heating due to the high current density even though there is no electrical arcing in the fabricated NEM switch. We observed no tip bouncing, as can be seen in Fig. 3(a). Figure 3(b) shows the magnified view of the pull-in region of the fabricated cantilever-type NEM switch. As soon as the voltage difference between the bottom electrode and the suspended beam surpasses 13.4 V, the electric current begins to rise rapidly to 10 nA. This abrupt switching with less than 3 mV/decade (based on the voltage step of 15 mV and the compliance current of 10 nA, practically infinite) represents ideal on/off current characteristics with an essentially zero off current and an excellent on/off current ratio exceeding 10^5, where the subthreshold slope is substantially lower than the theoretical limit (60 mV/decade) of CMOS devices at room temperature. Consequently, the proposed NEM switch can be considered very attractive for ultralow power applications due to its extremely low leakage current and abrupt switching characteristics.

Figure 4(a) shows *I-V* plot of the fabricated cantilever-type NEM switch ($w/L/t$=200 nm/300 nm/35 nm) under repeated dc bias sweep in air ambient. The fabricated NEM switch was successfully operated over 400 switching cycles near a pull-in voltage of 13 V with a pull-in voltage variation lower than ±1 V. Figure 4(b) shows the output current of the cantilever-type NEM switch ($w/L/t$

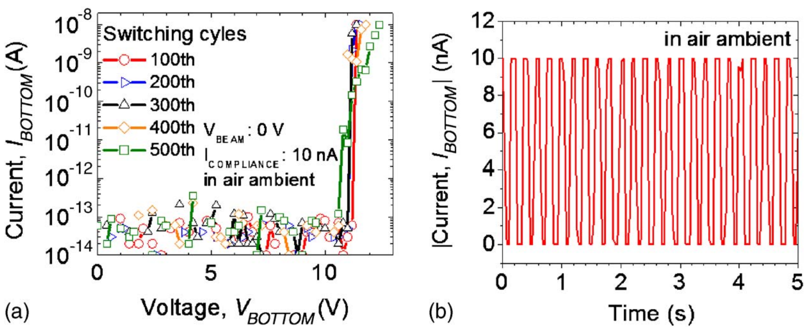

FIG. 4. (Color online) (a) *I-V* plot of the fabricated cantilever-type NEM switch ($w/L/t$ = 200 nm/300 nm/35 nm) under dc bias in air ambient. (b) The output current of the cantilever-type NEM switch ($w/L/t$=200 nm/300 nm/35 nm) as a function of time under ac bias in air ambient. Note that an ac bias with a peak voltage of 15 V and a square wave of 5 Hz were applied to the bottom electrode.

=200 nm/300 nm/35 nm) as a function of time under ac bias sweep in air ambient. Here, an ac bias with a peak voltage of 15 V and a square wave of 5 Hz was applied to the bottom electrode and a zero voltage was applied to the suspended beam. To our knowledge, this is the first demonstration of the NEM switch that can stably operate over several hundreds of switching cycles under dc and ac biases in air ambient. However, we also observed that the abrupt switching characteristics of the NEM switch often started to deteriorate over certain hundreds of switching cycles as the oxide insulating layer on the bottom electrode was physically damaged and eventually welded due to the accumulated Joule heat after repeated switching operations in air ambient. The endurance property appears to be greatly improved if the insulating layer with high melting temperature and strong hardness are used such as Al_2O_3 and HfO_2.

In summary, the cantilever-type NEM switch having a 15-nm-thick suspension air gap and a 35-nm-thick TiN beam was successfully fabricated using conventional top-down CMOS fabrication technology, and its characteristics were investigated for the first time. The fabricated cantilever-type NEM switch demonstrated ideal on/off current characteristics with an essentially zero off current, an abrupt switching with less than 3 mV/decade, and an excellent on/off current ratio of over 10^5 in air ambient. Furthermore, the cantilever-type NEM switch showed the repetitive switching operation of over several hundreds of switching cycles under ac and dc biases condition in air ambient. We hope this work would stimulate researchers to consider top-down approach positively to realize NEM switch, which can bring more benefit to mass production.

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