A Vertical MOSFET for Charge Sensing in the Convex Corner of Si Microchannels

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ABSTRACT

A vertical MOSFET formed in the convex corner of silicon microchannels is presented, which might be useful for detecting charged biomolecules. The cross type microchannels have four MOSFETs and four pairs of source/drain electrodes at each crossing. The non-planar and non-rectangular vertical MOSFET has an effective channel length of 20μm and an effective channel width of 9μm. The measured I-V characteristics of the vertical MOSFET exhibits a typical MOSFET behavior with a threshold voltage of –1.6V. Variation of drain current with time was also measured when the MOSFET was dipped into the thiol DNA solution. The drain current decreased and was saturated after 5 minutes, which we believe might be due to the change of threshold voltage caused by charged biomolecules adsorbed on the Au gate.

Keywords: vertical MOSFET, charge sensing, MEMS, microchannels, thiol DNA

1 INTRODUCTION

Numerous small multi-functional field-effect transistor (FET) based biosensors and chemical sensors for clinical or industrial demand have been developed [1]-[2]. Micro-fluidic prototype devices and systems have been also developed, specifically for portable diagnostic applications [3]. Except some limited cases such as pressure and acceleration sensors with the coupling between the measurement parameter and the sensor directly, many other components such as micro-fluidic elements or chemical sensors, should be operated in liquid. For less expense, instruments for drug discovery and medical diagnostics work with steadily decreasing sample volumes and increasing operating speeds. In order to meet this requirement, we propose the use of 3-dimensional vertical structure field-effect transistor in micro-fluidic channel which can be used in the integrated biochemical detection system. FET(field effect transistor)-type biochemical sensor, which is fabricated by the semiconductor integrated circuit technology, has attracted considerable attention because of its many advantages in miniaturization, standardization, mass-production and very proper configuration for smart sensor in which both sensor and measurement circuit are integrated. It is believed that 3-dimensional vertical FET type is the most suitable for combination with micro-fluidic channel.

In this study, we have fabricated 3-dimensional vertical metal oxide semiconductor field-effect transistor(vertical MOSFET) embodied in the convex corner which might be useful for detecting charged biomolecules in micro-fluidic channels. For fabricating the vertical MOSFET, we used TMAH solution, because the etchants must not contaminate the gate dielectrics with impurities such as mobile alkali ions, which shift the flatband voltage and affect the circuits otherwise [4]-[5], and it is relatively nontoxic and compatible with CMOS-based technologies. I-V characteristics of the vertical MOSFET were measured when it was dipped into the thiol DNA solution, in order to confirm the charge sensing capability.

2 FABRICATION

Figure 1 shows the schematic of the vertical MOSFET embodied in the convex corner of the silicon micro-fluidic channel. A trapezoidal micro-fluidic channel consists of several vertical silicon surface planes and the bottom surface of micro-fluidic channel by TMAH anisotropic etching process. The etch rate of (100) silicon surface and (111) silicon surface was about 0.27 μm and 0.009 μm per minute with TMAH 25wt.% solution at 70℃, respectively, and the anisotropy ratio of (100)/(111) was about 30 [6]. Particularly in the case of (100) silicon wafer, micro-fluidic channel with V-groove or trapezoidal shape can be fabricated by controlling the etching time and the width of the etching mask pattern.

As shown in Figure 1, the vertical MOSFET can be operated like a general planar type MOSFET. When a sufficiently larger voltage than threshold voltage is applied to the gate, the silicon surfaces is inverted and a conducting channel is formed between source and drain. If there is a voltage difference between them, current flows from the source to the drain. For application of gold-alkanethiol self-assembled monolayers, the Au/Cr layer was used for the gate metal of the vertical MOSFET [7]-[9].

In this study, the micro-fluidic channel and the 3-dimensional vertical PMOSFET(vertical PMOSFET) in the convex corner of the micro-fluidic channel were fabricated on n-type substrate. Key process steps of the vertical

PMOSFET are shown in Figure 2 and the fabrication process is as follows.

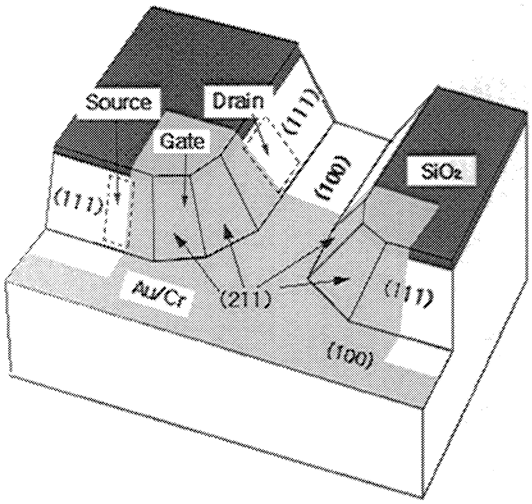

Figure 1: Schematic structure of the 3-dimensional vertical MOSFET.

The material used in this study were n-type {100} CZ grown silicon wafer with 1~3 Ω·cm resistivity. Initial oxide layer with a thickness of 5000Å was grown by thermal oxidation at 1100°C and the electrode line was defined using a first diffusion mask. The width of the minimum electrode line designed was 10 μm and the minimum distance between two electrode lines was about 21 μm. In the next process, the electrode lines were formed by the first boron diffusion process step for 24hours at 950°C using source wafer(BN1100), as shown in Figure 2(a). Next, the second mask with compensation pattern was used for micro-fluidic channel [10]. The width and the length of the compensate pattern were about 21 μm and 28 μm, respectively, as shown in Figure 2(b). The micro-fluidic channel with a depth of about 7 μm and a width of about 60 μm was formed by using anisotropic etching in the TMAH 25wt.% solution at 70°C. Simultaneously the compensation pattern was etched in the TMAH solution until the compensation pattern was removed and the angle of the convex corner was 90°, as shown in Figure 2(c). In the next step, source/drain were formed by second diffusion process step. At this step, the boron source was diffused only into bottom surface and vertical wall surface in the micro-fluidic channel because the thick initial oxide was remained on the other area, and the source and the drain on the convex corner were connected electrically. Using TMAH 25wt.% solution at 70°C, the second anisotropic etching was proceeded to remove about 1μm of (100) silicon surface. Then two (211) silicon surfaces were appeared in the convex corner, as shown in Figure 2(d). A 500Å thick gate oxide was grown by thermal oxidation at 950°C after removing the native oxide using buffered HF. After the via-

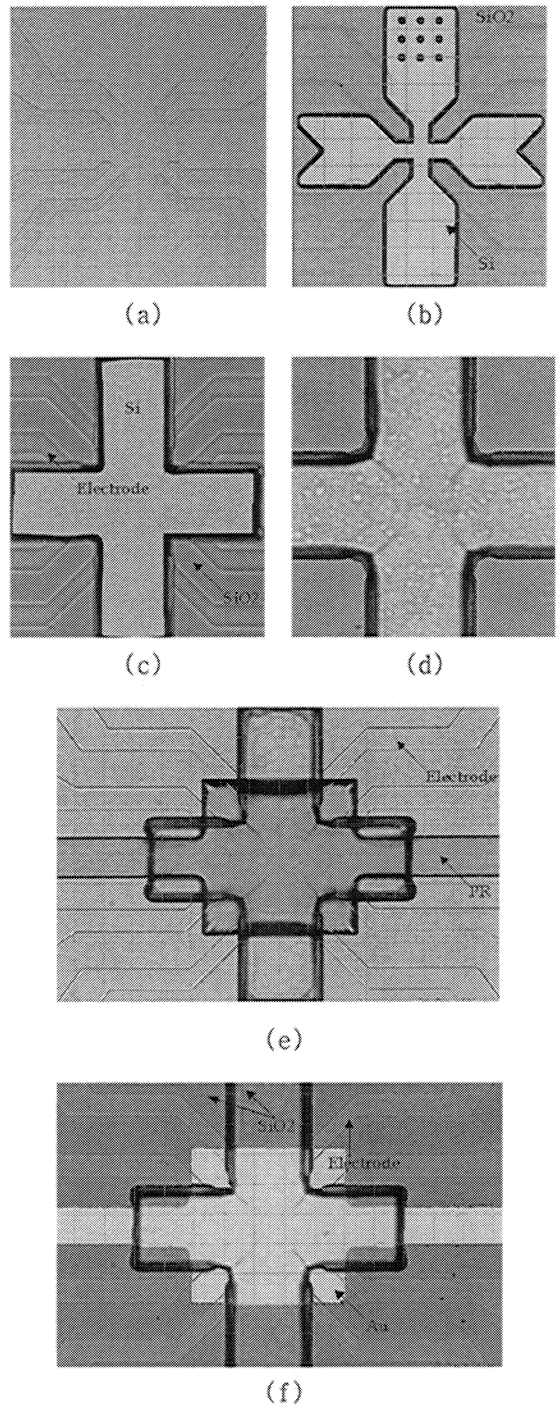

Figure2 : Optical microscope image of the key process steps for the fabrication of the vertical PMOSFET, (a) after first diffusion, (b) after definition of TMAH etch pattern, (c) after first TMAH etching, (d) after second TMAH etching, (e) after coating of AZ4620 PR, (f) fabricated micro-fluidic channel and the vertical PMOSFET embodied in four convex corners, gate electrode was formed by Au layer.

hole opening process using contact mask, a Au/Cr layer was deposited by sputtering. The thickness of Cr and Au layer were 200Å and 5000Å, respectively. To pattern pads, electrodes and gate metal in the deep channels, AZ4620 PR was coated, over-exposed and developed to make etching masks, as shown in Figure 2(e). Finally, Au/Cr layer was etched using Au and Cr etchant. The measured depth and top width of trapezoidal micro-fluidic channel depth and top width were about 8μm and 60μm, respectively, as shown in figure 2(f).

Figure 3 shows a optical microscope image of the fabricated trapezoidal micro-fluidic channel and the vertical PMOSFET embodied in four convex corners. The optical microscope image shows that a vertical PMOSFET with a gate length of approximately 20 μm was measured, and the gate width of about 9 μm was calculated. As a gate electrode, Au/Cr layer was used for four vertical PMOSFETs.

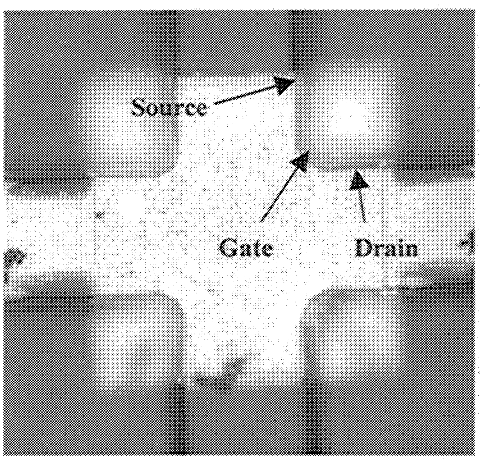

Figure 3 : Optical microscope image of the fabricated 3-dimensional vertical PMOSFET.

3 RESULTS AND DISSCUSSION

The device electrical characteristics of the vertical PMOSFET were investigated. The gate channel width and length of the vertical PMOSFET in the convex corner of the micro-fluidic channel are 9 μm and 20 μm, respectively.

Figure 4 shows measured and calculated drain current curves as a function of drain bias for various gate-source voltages for the devices with a common-source configuration. At V_{DS}= –5V and V_{GS}= –5V, the drain current and the transconductance of the device were –22.5 μA and 15 μS, respectively. The above values are smaller than general PMOSFET's because of the smaller mobility and the smaller effective W/L ratio. In the presented device structure, the gate width is shorter than the gate length because it is limited by the micro-fluidic channel depth. Silicon surface planes which are under the gate oxide consist of two different surfaces of (211) plane, as shown in Figure 1, and the TMAH anisotropic etching step roughens the silicon surfaces. Therefore, the bad surface quality decreases the mobility of the device.

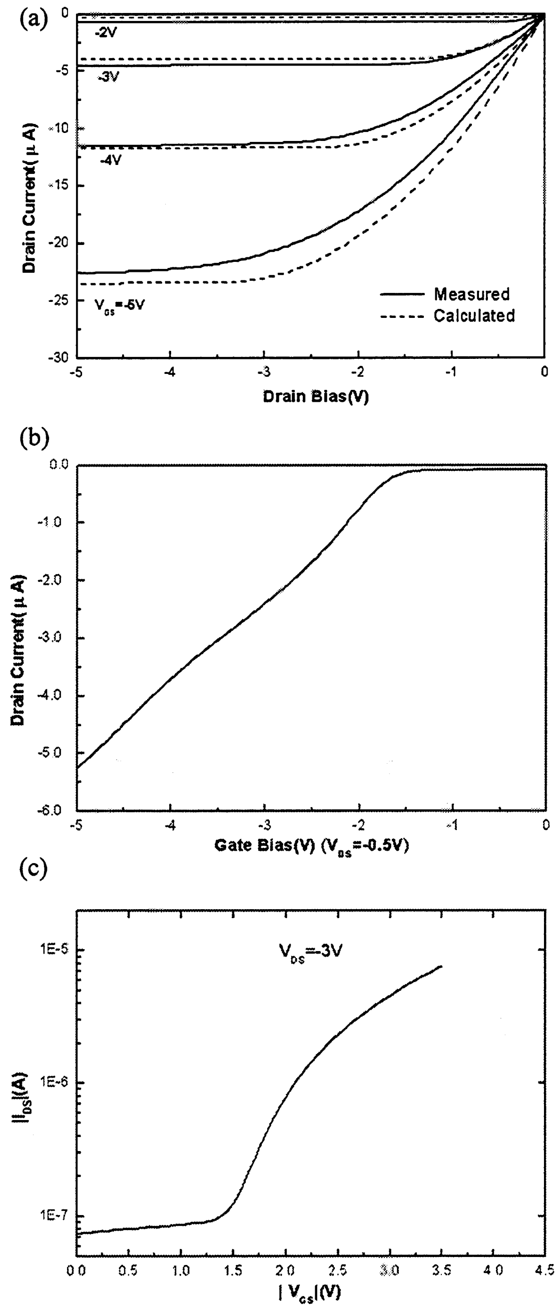

Figure 4 : Common-source drain currents of the vertical MOSFET, (a) I_{DS}-V_{DS} characteristics, (b) I_{DS}-V_G characteristics, (c) Subthreshold characteristics.

In order to compare measured drain currents with calculated values, we extracted the device parameters from the measured electrical device characteristics. The measured and calculated results for the vertical PMOSFET show good agreement. In our calculation, we approximated a two-dimensional device structure and calculated the drain current. The absolute value of the threshold voltage was larger than 1.5V, as shown in figure 4(b). It is because we omitted the threshold voltage adjust process and the threshold voltage can be adjusted to the desired value by adding the process.

The subthreshold characteristics of the vertical PMOSFET are shown in Figure 4(c). At $V_{DS}= -3V$, the subthreshold current was about –70nA and the subthreshold swing(S-factor) was 500mV/dec. The subthreshold current is comparatively large due to following reasons. One possible reason is that the source and the drain in the convex corner is not sufficiently separated by the TMAH etching process for the source/drain region definition. Another reason might be the leakage current caused by a large drain electric field. The S-factor was also larger than 100mV/dec, but it can be smaller as the gate oxide becomes thinner and as boron concentration of substrate becomes higher.

Variation of drain current with time was also measured when the MOSFET was dipped into the thiol DNA solution. As shown in Figure 5, the drain current decreased and was saturated after 5 minutes, which we believe might be due to the change of threshold voltage caused by charged biomolecules adsorbed on the Au gate.

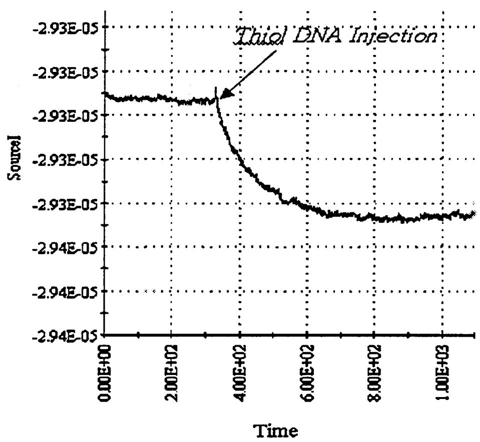

Figure 5 : Variation of drain current with time.

These results show that the vertical MOSFET embodied in the convex corner exhibits a reasonable electrical characteristics and might be useful for various sensors detecting charged biomolecules in the micro-fluidic channel since the Au gate has an affinity with thiol.

4 CONCLUSION

We have fabricated a vertical PMOSFET embodied in the convex corner of the silicon micro-fluidic channel. The top width of the micro-fluidic channel is about 60 μm and the depth is about 8 μm. In the convex corner of the micro-fluid channel, the vertical MOSFET consists of nonplanar gate with two different (211) surfaces and source/drain with the different (111) surfaces. The drain current and the trans-conductance at $V_{DS}= -5V$ and $V_{GS}= -5V$ were –22.5μA and 15μS, respectively. The device characteristics exhibit a typical MOSFET behavior. The drain current decreased and was saturated when the vertical MOSFET was dipped into the thiol DNA solution, which we believe might be due to the change of threshold voltage caused by charged biomolecules adsorbed on the Au gate. It is concluded that the vertical MOSFET embodied in the convex corner might be useful for various sensors detecting charged biomolecules in the biochemical solutions.

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