AN INTEGRATED CIRCUIT DESIGN FOR SILICON-NANOWIRE READ OUT CIRCUIT

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ABSTRACT

A measurement method for poly-silicon nanowire field-effect transistor (SiNW FET) is proposed and the read-out circuit for realizing the method is designed. The method helps to mitigate the device mismatch problem. The problem is common and mostly caused by the fabrication variance. The method utilizes the linearity relation between device current (I_{ds}) and transconductance (gm). During the measurement, the current of nanowire is kept in a fixed value, which means gm of device is constant as well. By controlling the gm of mismatched devices to be same, the devices produce same output current when the testing biomolecule concentration changes. The current variance is then transformed into voltage and that voltage is amplified in the end.

This article shows the design concept, circuit schematic, table of specification and chip measurement results.

1. INTRODUCTION

Poly-silicon nanowire(SiNW) is an interesting one-dimensional nano-structures. Many research of fabrication and electrical properties have been conducted [1]. Since it was first introduced to the biosensor field in 2001 [2], it has become a promising candidate for ultra-sensitive, real-time and label-free sensor device.

One of the challenges of nanowire is the device variability problem caused by fabrication variation. The problem results in the device mismatch for devices fabricated in the same process. For our nanowire (Fig.1), the problem exists and effect the measurement severely.

In this work, a measurement method aimed to solve the problem is proposed, and the read-out circuit for realizing the method is designed. The results presented in the end of this work show the method effectively mitigate the problem.
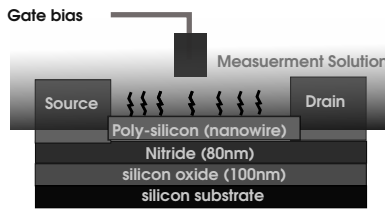

Fig. 1. Nanowire device Structure

1.1. Constant-Current Constant-Transconductance

For a simple MOSFET, its transconductance(gm) is related to its drain-to-srouce current (I_{ds}).

$$\text{Strong inversion region: } \sqrt{2I_{ds}(\kappa\mu C_{ox}\frac{W}{L})} \qquad (1)$$

$$\text{Weak inversion region: } \frac{\kappa I_{ds}}{\phi_t} \qquad (2)$$

ϕ_t is the thermal voltage. κ is the gate coupling coefficient that is 1 in strong inversion and approximately between 0.4 to 0.7 in weak inversion. This κ for nanowire in weak inversion is believed to be close to 1 since the aqueous capacitance is far larger than the capacitance of silicon substrate. Based on the equation, we believe that the gm of nanowire can be determined by its I_{ds}.

1.2. Proposed Measurement Method and Read-out circuit

According to the last section, the gm of mismatched nanowire devices can be adjusted to the same value by controlling their I_{ds}. In this works, the changes of the biomolecule concentration is taken as an equivalent ΔV_G. Thus, a ΔV_G should produce same current response (ΔI_{ds}) for mismatched device whose gm are same.

This method is realized by our read-out circuit. The circuit first performs DC sweep (Fig.2(a)) to find the I_{ds}-V_{gs} curve of each device under test (DUT) (FIg.2(b)). The I_{ds}-V_{gs} curve of DUT is then transformed into gm-I_{ds} curve (Fig.2(c)). With these curves, the corresponding I_{ds} values are found. During each measurement, DUTs are always initialized with their specific I_{ds} by adjusting the V_{gs} in the end of each measurement task.
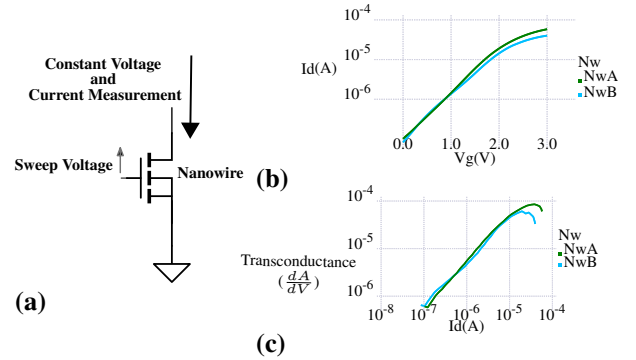

Fig. 2. **(a)** DC sweep. **(b)** I_{ds}-V_{gs} curves. **(c)** gm-I_{ds} curves.

1.3. Architecture

The constant current structures such as source follower have been applied to several works of ion-sensitive field-effect transistor(ISFET) [3], which is a relative of SiNW. A similar structure is presented here. The structure can switch between two modes: DC-sweep mode (DC mode)(Fig.3(a)) and Transient Measurement mode (Tr mode) (Fig.3(b)).

Operation in DC mode is similar to Source follower. Except the negative feedback doesnt happen at source but gate through feedback loop circuit. This mode devotes to set up nanowire in the beginning when the reference ion solution is given.

Tr mode is used after suitable gate voltage is found in DC mode. In this mode, the feedback loop is removed and the tested solution is then given. The difference of the concentration of biomolecule results in an equivalent ΔV_G at gate. A variance of current is induced and is converted to output by a transimpedance(TIA) and a voltage amplifier.
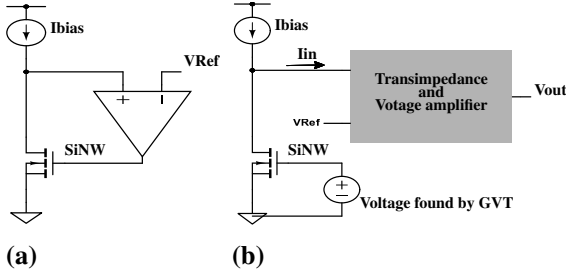
Fig. 3. Circuit block diagram of **(a)** DC mode **(b)** Tr mode.

2. CIRCUIT IMPLEMENTATION

Fig.4 shows the circuit schematic. DC mode and Tr mode shared a common transimpedance(TIA), which is resistor-based because linearity is necessary for a wide input current range (from 10nA to 1uA). This TIA block transduce ΔI_{ds} into a voltage signal while keeping the V_D of the nanowire constant. A controlling switch switches manually between integrated circuit and an external voltage source(Vb) that can memorize the voltage obtained by DC mode.

For DC mode, an open loop OP connected to the output of TIA. It is used as a low pass filter with bandwidth < 20Hz. It introduces only DC or low frequency signal into the feedback loop. Besides, the low frequency dominant pole it creates can keeps the feedback loop stable when sometimes the large transconductance of nanowire increases total loop gain a lot.

For the Tr mode, the output of TIA connected to an analog subtractor which is for shifting the offset voltage from V_{Ref} to V_z. It is then followed by a non-inverting resistor-based amplifier. This amplifier has amplification rate of 100. It amplifies the voltage difference between the output volatge of TIA and the reference voltage.
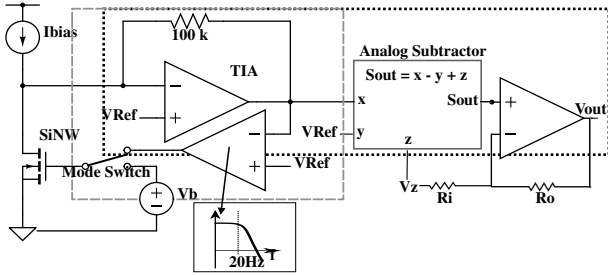

Fig. 4. Schematic of the read-out circuit

3. CHIP MEASUREMENT AND RESULTS OF THE METHOD

Fig.5 is the photo of our read-out circuit. The circuit is fabricated with the TSMC 0.35um process and has 8 units of read-out circuit on a single chip. Its characteristics are shown in Table.3.

The circuit of DC mode is able to measure device with gm from 3μ to 20μ. The lower bound of this range can be further decreased. An input mismatch problem occurs in the open loop OP due to fabrication variance. It can be solved in the future by improving the layout or modifying the structure. The Tr mode has total amplification rate of $8.9M$ ($G_{TIA} \times A_{amp}$). It also has a very low input-referred noise. For our nanowire, the maximal noise is $0.3nA$ when referred to I_{ds} (Fig.6), which is far lower than the equivalent ΔI_{ds} that biomolecules can induce. Besides, the fastest signal speed it can detect is $7.5kHz$, which is enough for most biological experiments.

In Fig.7, the results of the proposed measurement method is presented. The biomolecule testing solution is a pH buffer and the reference solution is double-distilled water. The method is applied to two nanowire devices with device mismatch. There I_{ds}-V_{gs} curves are obtained (Fig.7(a)) and gm-I_{ds} curves are computed (Fig.7(b)). The Fig.7(c) shows that the problem is mitigate. Two devices exhibit similar
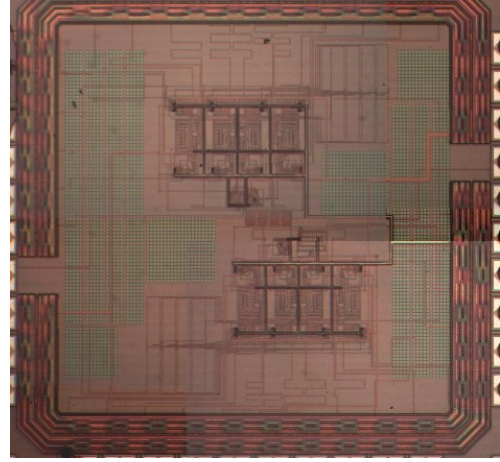

Fig. 5. Chip fabricated by TSMC 0.35μ process.

| VDD	3.3v
Power Consumption	1.48mW
Size	1.57 x 1.57 mm^2
DC sweep mode	
SiNW transconductance Range (gm)	$3\mu \sim 20\mu$
SiNW Bias Current Range (I_{ds})	$1\mu A \sim 50\mu A$
SiNW Gate Voltage Range (V_{gs})	$0.45v \sim 3v$
Transient measurement mode	
Input current to Output voltage gain	8.9M
ΔI_{ds} detecing Range	$2.8nA \sim 5.3\mu A$ $-15\mu A \sim -2.8nA$
Maximal Signal Detection Speed(Hz)	$7.5k$
Maximal Input Reffered Noise(mV)	$0.3nA$

Table 1. Specification Summary
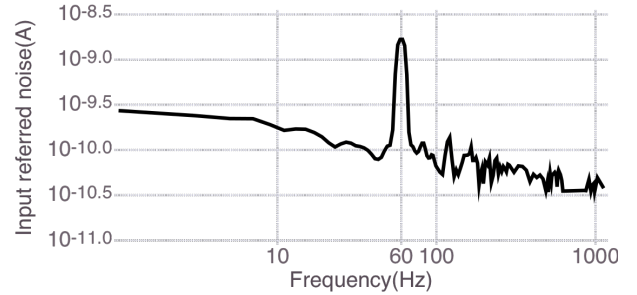
Fig. 6. The power spectral density of input referred noise. The 60Hz noise comes from the environment and working machines. It can be further reduce by adopting better method of experiment or equipments.

responses with error less than 8%. This error should be experimental error.

4. CONCLUSION

In summary, our method and circuit mitigate the device mismatch problem. The circuit can be improved in the future by introducing digital circuit. In that way, the gm-I_{ds} curve obtaining and mode deciding can be automatic, and a systematical measurement architecture can be built.
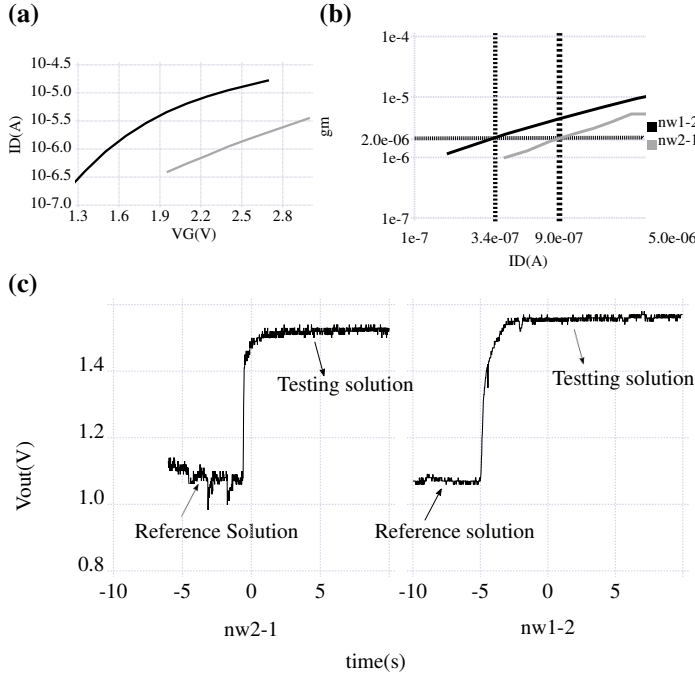
(a)

(b)

(c)

Fig. 7. Proposed measurement method applied to two mismatched devices (nw1-2 and nw2-1). **(a)** Their I_{ds}-V_{gs} curves. **(b)** Their gm-I_{ds} curves. **(c)** The output responses when the testing solution (pH6 solution) is added into reference solution (double-distilled water).

5. REFERENCES

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