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Miniaturized 3D gas sensors based on silicon nanowires for ppb range detection

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Abstract— Here, we reported 3D devices implemented on silicon nanowires (SiNW) for chemical gas sensing, working at room temperature and in presence of moisture or interfering gas. This sensor combines for the first time high sensibility, selectivity, reversibility, low-power consumption and reliability in real condition. In addition the sensors are miniaturized and develop through a cost effective and large scale approach.

I. INTRODUCTION

Current trends go towards embedded multifunction systems. The most notable case is the evolution of mobile phones which resulted the smartphone: a “tool” with many uses where new sensors are integrated to add new functionalities. In that context, gas sensors would be implemented in order to monitor, during all day long, the air quality in polluted urban environments as the concentration of nitrogen dioxide (NO_2), or detect domestic gas leaks. However this requires a reorientation of the sensor industry towards components more and more miniaturized to reduce weight, size, power consumption and price. Currently commercial sensors use a metal oxide as sensitive layer on a micro hotplate technology. These devices are relatively large ($\approx 1\text{-}10\text{ mm}^2$) and require high power consumption for supplying the heater (mW range). In addition, they demonstrate low selectivity and sensitivity to high concentrations of gas ($>1\text{ ppm}$), out of step with the recommendations of the various environmental agencies to long period exposure thresholds (50 ppb NO_2 [1]). In that context, the integration of 1D nanostructures, thanks to their high ratio surface/volume, have been proposed to improve the sensitivity and detection limit [2], [3]. However, despite numerous studies of nanowire devices, any demonstration presents satisfactory operation [4], [5] at very low concentrations. Here, we propose a 3D sensor architecture based on silicon nanowires networks of (Figure 1). The 3D configuration improves the free surface for gas adsorption in order to enhance the sensitivity, and decrease the detection limit.

II. DEVICE FABRICATION

This approach is compatible with silicon processing using conventional microelectronics tools, allowing the potential

co-integration of these sensors with CMOS devices. The transduction is based on resistor configuration where the nanowires bridge the positive and negative electrodes to allow current flow. The device conductance change is monitored.

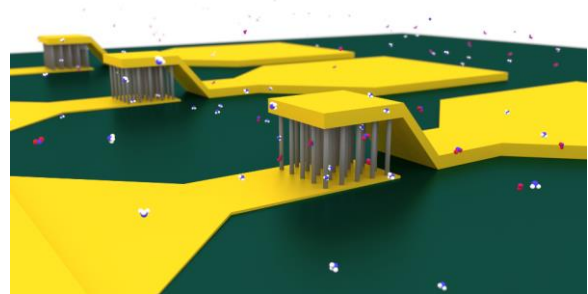


Figure 1: Illustration of the 3D sensor architectures implemented on vertical NW arrays.

The fabrication process is large scale, reproducible and straightforward, and can be summarized in 3 steps: (i) firstly the nanowire networks patterning, (ii) secondly the bottom electrical contacts fabrication, and (iii) finally the top contacts structuration. A top-down approach has been developed (Figure 2.a-e) to perfectly control all the parameters of NW networks (diameter, height, spacing and the numbers of nanowires...).

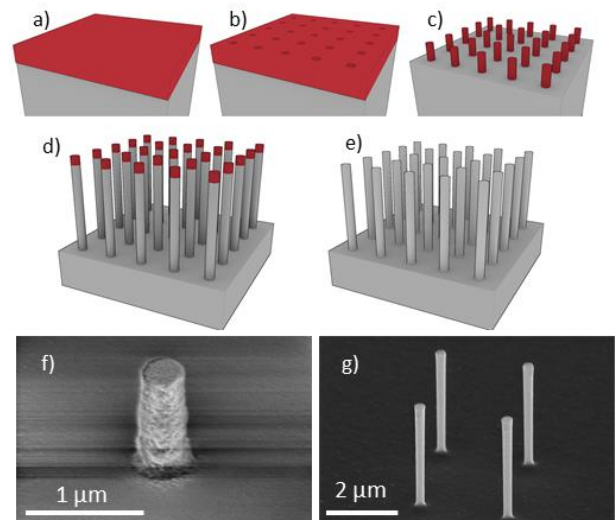


Figure 2: a)-e) Top-down fabrication of vertical nanowires network, SEM pictures of f) a resist nanodot and g) nanowires

An approach combining photolithography, plasma etching and sacrificial oxidation is developed to pattern the vertical nanowire networks. The first step consists of substrate patterning by photolithography (i-line stepper), to achieve array of resist nanodots (Figure 2.a-c, f). Then the patterns are transferred into the bulk silicon by deep reactive ionic etching (DRIE) (Figure 2.d). Finally remaining resist is stripped and a sacrificial oxide layer is grown to tune precisely the nanowire diameter (Figure 2.e, g).

The device is composed of two symmetrical aluminum contacts at each end of the NWs. The top contact is obtained by an "air bridge" approach of allowing the definition of a three-dimensional connection to the NW top (Figure 3). For the top and bottom contacts, a standard etch-back process is used. However for the top contact, a sacrificial material is employed to connect only the top of the nanowires, leaving the rest of the surface available to react with gases.

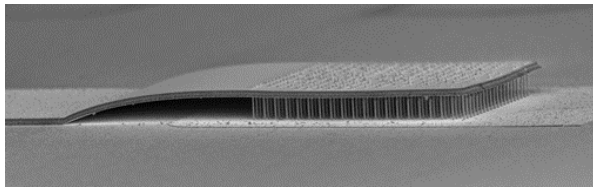


Figure 3: SEM picture of the sensor : a side view of one array of vertical silicon nanowires, contacted electrically by an air-bridge structure

III. RESULTS AND DISCUSSION

Under controlled atmosphere, the device demonstrates excellent gas sensing performances. A typical gas response curve is presented in Figure 4. When NO_2 is injected, the resistance of the sensor decreases, but when the gas injection stops, the resistance returns to the base-line. The sensor recovery occurs naturally at room temperature, and does not require specific conditions such as UV illumination [4] or flushing [5]. For ammonia, an opposite response was observed: the resistance increases, contrary to NO_2 case. Moreover the response of carbon monoxide (CO) and propane (C_3H_8) have been investigated: in both case there are no response of the sensor. This demonstrates the selectivity of the device, by discriminating NO_2 and NH_3 , without being interfered with CO and C_3H_8 .

Due to the enhanced adsorption surface conferring by the 3D configuration, extremely low sensibility level has been reached. A very high response (30%) is obtained at 50 ppb of NO_2 (the dilution limit of our test bench), in comparison of the 25% reached for 200 ppb in [4], indicating that the limit of NO_2 detection by our device is greatly below 20 ppb.

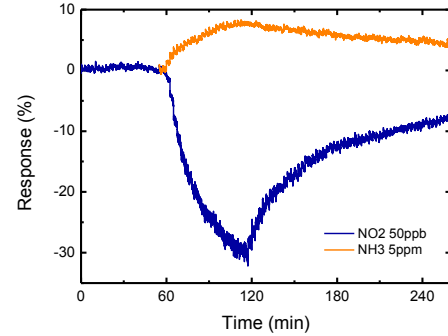


Figure 4: Response of the device to 50 ppb of NO_2 (blue) and 5 ppm to NH_3 (orange)

In addition, the sensors retain their outstanding performance in real working condition. In particular, we demonstrated that they are not disturbed by the presence of moisture (tested up to 70% of relative humidity), one of the major drawbacks of metal oxide-based gas sensors. The device is sensitive to humidity and NH_3 , but in presence of NO_2 (even for low concentration) the detection mechanism of NO_2 dominates the others mechanisms (moisture and interfering gas).

IV. CONCLUSION

In summary, we demonstrated record detection of NO_2 down to ppb level, using resistor gas sensors based on 3D SiNW networks. This device combines for the first time high sensitivity, selectivity, reversibility, low-power consumption, no poisoning by humidity, reliability, miniaturization, cost effective, large scale and CMOS compatible fabrication, and open the way of new possibilities for integration of unidimensional nanostructures for very sensitive embedded sensors.

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