Photoconductivity of Interconnected Nanowires and Their Electromagnetic-Circuit Co-Simulation

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***Abstract*—Nanowires made of different materials, namely zinc oxide and vanadium oxide, are interconnected mechanically with the aid of a sharp tungsten tip. The electrical and optoelectrical properties of the interconnected nanowires are measured. The changing photocurrent as a function of laser beam spot location is verified via electromagnetic/circuit co-simulations.**

I. Introduction

The temperature dependent photocurrent generation of the semiconducting nanowires has been one of the most popular subjects in the are of nano opto-electronics due to their compelling electronic, mechanical and optical properties in the last two decades (Y. Cui and C.M. Lieber, Science 291, 851 2001). Zinc oxide (ZnO) and vanadium oxide (VO_2) are two of the most heavily studied materials due to their large band gap and metal-insulator transition at temperature of 68° C, respectively. Putting these two materials in the same network is interesting and might be important because of two reasons. First, they have totally different mechanisms behind their semi-conducting nature. Second, using nano-wires made of different materials enables additional control of photo-induced current generation in such nano-networks. In this work, we experimentally and numerically study interconnected ZnO and VO_2 nanowires.

II. Methods

The nanowires are grown in a horizontal tube furnace by following the recipe (provided in B. Mukherjee *et al.*, J. Cryst. Growth 346, 32–39 2012). Prefabricated Au electrodes are patterned on top of the SiO_2/Si substrates under two-probe configuration using standard optical lithography techniques, where oxide thickness is 300 nm and substrate is n-type. The nanowires are placed between the Au electrodes using a micromanipulator probe station with the help of a sharp tungsten tip. To form cross-junction between two nanowires, one nanowire is transferred on top of the other nanowire, such that they form cross shape structure. Au electrodes are connected to semiconducting nanowires through Pt nanowires with the help of a focused ion beam system.

The electrical measurements are carried out in ambient conditions using a Keithley 6430 sourcemeter under sweeping and fixed bias modes. The details of the photoconductivity measurement setup can be found in (B. Mukherjee *et al.*, J. Appl. Phys. 114, 134302 2013). Briefly, laser beam is focused into a region with 1-3 μm diameter with an objective lens. Local photoconductivity (I-t) measurements from the device is obtained under fixed bias condition by irradiating the focused laser spot at different parts of the device with multiple laser on/off states in fixed time interval.

III. Experiment and Simulation Results

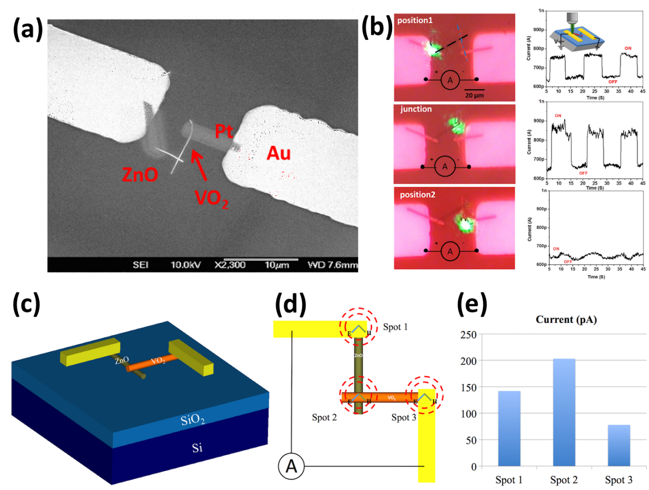

Fig. 1. (a) An SEM image of interconnected nanowires. (b) Optical images showing the focus of laser excitation and corresponding photocurrents. (c) 3D and (d) 2D of views of the simulated geometry. (e) Photogenerated current simulation results.

We first study individual ZnO and VO_2 nanowires experimentally. Since I-V curves are not linear, it is not possible to make a one-to-one comparison but we observe that the latter produces much higher current. The current increases with voltage and temperature as expected. The increase with applied potential is almost linear for VO_2 nanowire within $\pm$ 20 mV range; whereas ZnO nanowire as two different regimes intersecting at ~ 0.2 V.

Then we study interconnected ZnO and VO_2 nanowires. We first observe increasing conductance with temperature, which is typical for semiconductors. Second, we observe photocurrent increases with the laser power. Third, the work function difference in ZnO and VO_2 creates a current even if there is no illumination. Last but not least photocurrent changes if we change the location of the focused laser beam. In order to verify these observations, we run a set of simulations using Wavenology, which is a commercial FDTD full-wave electromagnetic/circuit co-solver. Fig. 1 (c) shows a schematic of the simulated structure: orange and green cylinders represent VO_2 and ZnO nanowires, respectively on top of SiO_2/Si substrate.

Each nanowire is assumed 1 μm long and electrodes are made of perfect electrical conductors as represented by yellow bars. Refractive indices of VO_2 and ZnO are taken as 1.789+0.145i and 2.13+0.59i, respectively. The refractive indices of Si and SiO_2 are taken from (E. D. Palik, Editor, Handbook of Optical Constants of Solids, vol. 1, Academic Press Publishers, 1985). The geometry is illuminated from the top with a green laser beam ($\lambda = 532$ nm), where the beam aperture is assumed to be 2 μm. Similar to the experiment, we run three set of simulations, where we change the beam axis position as shown in Fig. 1 (d), and calculate the current flowing through an infinitely thin PEC wire between the PEC electrodes.

Fig. 1 (e), the current decreases when the spot is changed from VO_2-electrode intersection to ZnO-electrode intersection and the maximum current is observed when the laser is focused onto the intersection of nanowires. The ZnO nanowire's low polarizability with respect to VO_2 nanowire explains the first observation and the second observation simply states that the total induced current increases as we increase the volume of the object that is partially illuminated with electromagnetic (optical) waves. Based on the good agreement between experimental and numerical results, we can conclude that the amount of generated photocurrent heavily depends on dimensions, mutual positions, and material compositions of nanowires. The further details of the co-simulations will be discussed at the conference.

IV. Conclusion

Interconnected semiconducting nanowires fabricated over silicon wafers are characterized opto-electronically. Measurements confirm (i) existing of dark current due to work function difference between zinc oxide and vanadium oxide, (ii) increasing conductance with increasing temperature and potential, and (iii) dependence of photocurrent on the location of focused laser beams. Experimental results are verified via electromagnetic/co-circuit simulations.