Lifetime of Charge Carriers in Single Silicon Nanowire

Jhim Handrex Meza
Electrical Engineering, University of California, Los Angeles, CA

NNIN REU Site: Center for Nanoscale Systems, Harvard University, Cambridge, MA
NNIN REU Principal Investigator(s): Prof. Kenneth B. Crozier, School of Engineering and Applied Sciences, Harvard University
NNIN REU Mentor(s): Dr. Yaping Dan, School of Engineering and Applied Sciences, Harvard University
Contact: handrex@ucla.edu, kcrozier@seas.harvard.edu, yapingd@seas.harvard.edu

Abstract:

The lifetime of charge carriers is one of the key parameters that determine the performance of semiconducting optoelectronic devices. However, due to their small size, the lifetime in silicon nanowire (SiNW) devices may be very different from their conventional bulky counterparts. We therefore investigated this difference during the REU program. We measured the charge carrier lifetime of a single SiNW indirectly using SPCM and found the electron lifetime to be a few orders of magnitude smaller than that in a Si bulky device.

Introduction:

In the past several decades, complementary metal oxide semiconductor (CMOS) technology has created many sophisticated devices and systems such as computers, cell phones, cameras and many other electronics. CMOS has changed almost every aspect of our life. These extraordinary technological advances are realized by constantly scaling down the size of CMOS transistors and integrating more and more devices on chip. However, when the size reaches into nanometer scale, CMOS technology encountered tremendous challenges, and nanotechnology may be able to provide solutions to those challenges.

Research in nanotechnology in the past decade has focused mainly on novel devices and concepts. In fact, the performances of nanodevices are equally important. Any performance of a device has a collective balance of physics behind it. Nanodevices have introduced their low dimensionality as a factor that may break this balance. In certain cases, this balance breakdown is favorable for improving the performance. For example, nano chemical gas sensors generally have higher sensitivity than their bulky counterparts because nanosensors have more surface areas that can interact with analytes. In many other cases, this may not be true. The lifetime of charge carriers in nanooptoelectronic devices fall into this latter category.

Methods:

In this summer REU program, we first used the standard photolithographic processes to electrically contact an SiNW, and then employed scanning photocurrent microscopy (SPCM) to measure the lifetime indirectly.

The p-type SiNWs (mostly 70 nm diameter) used in the experiments were synthesized at 460°C using Au NPs as catalysts by the VLS method. The SiNWs were made into a suspension after sonication and purification by a centrifuge. The wires were randomly spread from the suspension onto a Si/SiO_2 substrate with prefabricated alignment markers. The position of the NWs were located under the optical mask aligner using those markers.

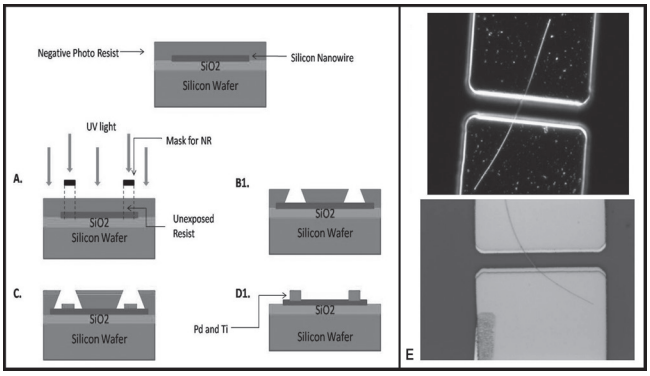

Figure 1: Nanofabrication process. A. During exposure, B1. After develop, electrodes in contact with nanowire ends, C. Coating with Ti and Pd, D1. After lift-off. E. SEMs of nanowire contacted with metals at both ends.

In Figure 1, we used a negative resist NR9 and liftoff process to make 180 nm thick palladium electrodes (using 2 nm thick titanium as the adhesion layer) that contacted single wires. The fabricated NW devices, with a Schottky barrier at each end, were electrically responding to light. SPCM uses a nanosized laser (through a near-field scanning optical microscopy, or NSOM, tip) to scan over the NW and excite the charge carriers, as shown in Figure 2.

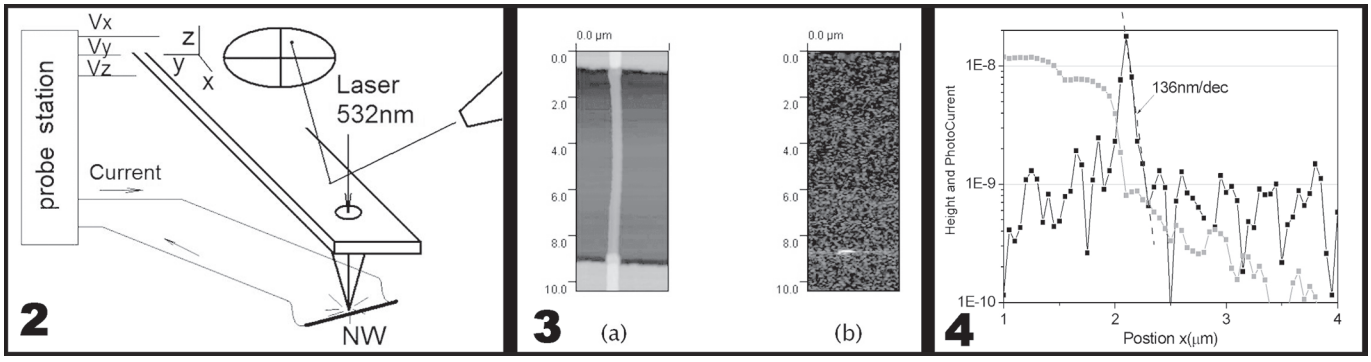

Figure 2: Schematic of SPCM.

Figure 3: (a) AFM image of nanowire with a diameter ~ 53 nm, and (b) the corresponding scanning photocurrent map where a brighter color represents a larger photocurrent.

Figure 4: Photocurrent in logarithm scale versus the position of the laser beam.

We applied a few volts as an electrical bias on the NW device. Due to the Schottky barriers, the bias mainly dropped over the barriers and only a very small fraction was on the NW bulk. In this case, the bulk NW was almost free of electric fields. Therefore, the locally excited charge carriers diffusively decayed from the laser location to the anode electrode and were eventually collected as photocurrent.

The position of the laser and the photocurrent, that were recorded simultaneously, followed the equation, $I_{ph} \sim \exp(-x/L_n)$, where I_{ph} is the photocurrent, x the distance and L_n the diffusion length. From this position-photocurrent relation, we could extract the diffusion length of charge carriers L which was related to their lifetime τ as $L = \sqrt{D\tau}$ where D is the diffusion coefficient.

Results:

The atomic force microscopic (AFM) image and a photocurrent map obtained from SPCM are shown in Figure 3. The photocurrent line profile along the NW can be obtained by drawing a line near the Schottky barrier at the bottom electrode where there was a photocurrent peak (Figure 3b). To ensure the photocurrent line profile was directly on top of the NW, a second line could be drawn in the AFM image (Figure 3a). Both lines were starting from the bottom.

We plotted these two lines in Figure 4 with the light grey for the AFM profile and the black for the photocurrent profile. The light grey line tells us that the photocurrent peak was right near the electrode. The Schottky barrier was buried under the metal electrode, which was not transparent and therefore blocked the laser. Therefore, no photocurrent was observed, as the NSOM tip was on the electrode initially. The laser excitation on the NW increased rapidly while the NSOM tip was moving up. For this reason, we observed a steep elevation in photocurrent. When the tip was further moving away from the electrode, the photocurrent quickly decayed because of the recombination of excited charge carriers when diffusing toward the electrode. This decay slope was closely related to the diffusion of charge carriers. According to the equation aforementioned, we were able to extract the diffusion length if the photocurrent was plotted in a logarithm scale.

In Figure 4, the right decay slope is 136 nm per decade, which corresponds to a diffusion length ~ 55 nm. The lifetime of the charge carriers in this SiNW was calculated to be ~ 100 ps, which is three to four orders of magnitude smaller than that in silicon bulk. From the AFM image in Figure 3a, the NW diameter is approximately 70 nm. The diffusion is roughly equal to the size of the NW diameter. Larger sized NWs have longer diffusion lengths, which is true for many other NW devices, as we observed.

Conclusions:

We find the electron diffusion lengths in silicon nanowires are very short compared to those in bulk silicon and are closely related to the NW diameters. Considering that the smaller NWs have a higher density of surface recombination sites, the short diffusion lengths of charge carriers in NWs likely originate from the surface recombination [1]. This hypothesis is still under investigation.

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