Measuring Resistive Characteristics of Silicon Nanowire by Applying Electrostatic Tensile Device and Broadband Test Signal

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ABSTRACT

Nanostructures can show mechanical and electrical properties that are remarkably different from their bulk forms. Thus, physical properties of nanostructures need precise experimental evaluation when being used as a functional component in nanoelectronic device or nanoelectromechanical system. Ohm's law, which is typically used to calculate the resistance of a bulk conductor, does not apply for nano structures due to the various effects brought on by the finite size effect. It has been shown that the resistivity of the wire increases when the size decreases as a result of surface scattering. This paper extends the studies and investigates how the resistive characteristics vary when the nanowire is stretched. An electrostatic actuating tensile device is applied and the resistive characteristics are evaluated by means of maximum-length pseudo-random binary sequence (MLBS) and Fourier techniques. The results reveal unreported characteristics of the applied nanowire. The wire resembles almost an ideal resistance within the bandwidth of the applied devices, and shows remarkable change in the resistance as the stretching force is varied; higher stretching force yields higher value in resistance.

Keywords: Silicon nanowire, frequency-domain characterization, resistance, excitation design

1 INTRODUCTION

Silicon nanowires have attracted significant attention by the electronics industry due to the need for ever-smaller electronics components and devices [1,2]. It has been shown that nanostructures reveal physical properties that are significantly different compared to the bulk forms of the structures. This physical phenomenon is called the nano-size effect, which is originated from the geometries and high surface-to-volume ratio of nanostructures [3–5]. Due to the nano-size effect, physical properties of nanostructures need precise experimental evaluation when being used as a functional component in nanoelectronic device or nanoelectromechanical system (NEMS).

Among all kinds of physical properties of nanomaterial, mechanical and electrical properties are the two most important ones. Most applications of nano devices are more or less under some sort of mechanical stress. Therefore, determination of electrical properties of nanostructures under varying mechanical stress can essentially help to understand how mechanical stress is affecting the electrical property of a nanostructure, which then decides the performance of the particular nanodevice.

Silicon is the main material for developing nanodevices. There have been several studies focusing on measuring resistance of silicon nanostructure and exploring the piezoresistive effect [6, 7]. To the best of authors' knowledge, there has been hardly any research on dynamic electrical characterization of silicon nanostructure under varying mechanical stress. There is, however, a strong need for methods of such characterization. One good example is a silicon-nanowire-based field-effect transistor whose performance is strongly dependent on the mechanical and electrical properties of the nanowire [8].

Ohm's law, which is typically used to calculate the resistance of a bulk conductor, does not apply for nano structures due to the various effects brought on by the finite size effect [9, 10]. It has been shown that the resistivity of the wire increases when the size decreases as a result of surface scattering. This paper extends the studies and investigates how the resistive characteristics vary when the nanowire is stretched. In this paper, an electrostatic actuating tensile device developed at Shanghai Institute of Microsystem and Information Technology in Chinese Academy of Sciences is applied to stretch a silicon nanowire and the electrical characterization is performed by means of broadband excitation and Fourier techniques. It may be assumed that a nanostructure does not follow ideal resistive characteristics in the whole frequency band. Hence, the measurements are performed in the frequency domain. The applied test signal (voltage over the nanowire) is maximum-length pseudo-random binary sequence (MLBS) which is a periodic signal containing energy at several frequencies [11]. The frequency-domain characterization of the resistance of the nanowire is obtained by measuring the resulting current over the nanowire and applying Fourier methods [12]. The challenges of the methods include extreme fragility of the stretched nanowire, design and generation of the excitation signal, and data acquisition due to an extremely low signal levels (nano amperes). The contribution of the paper is twofold. First, it shows that the resistive properties of a nanowire changes as the wire is stretched. Second, the paper provides methods for a comprehensive analysis to reveal electrical properties of a nanowire.

The rest of the paper is organized as follows: Section 2 reviews the basic theory applied in the paper and introduces Fourier methods in system identification and the synthesis of the MLBS excitation. Section 3 presents experimental measurements based on silicon nanowire. Section 4 draws conclusions.

2 METHODS

Consider a silicon nanowire acting as a linear time-invariant system for small disturbances in terms of applied voltage and current. According to basic control theory, this type of system can be fully characterized by its impulse response, which can be transformed into frequency domain and presented by a frequency-response function (FRF).

Fig.1 shows a typical setup where the device under test (DUT), presented by the system's impulse-response function $g(t)$, is to be identified. The DUT is perturbed by the excitation $x(t)$, which yields the corresponding output response $y(t)$. The measured signals are corrupted with noise and nonlinearities, as presented by $e(t)$ and $r(t)$. The measured excitation and output response can now be denoted by $x_e(t)$ and $y_r(t)$. The noises are assumed to resemble white noise and are uncorrelated with $x(t)$ and $y(t)$. All of the signals are assumed to be zero mean sequences.

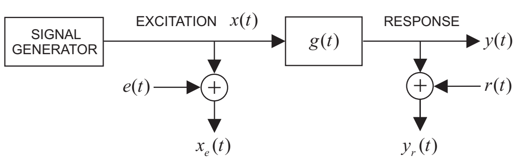

Figure 1: Typical FRF-measurement set up.

The FRF of the DUT can be denoted as

$$G(j\omega) = \frac{Y(j\omega)}{X(j\omega)} \tag{1}$$

where $Y(j\omega)$ and $X(j\omega)$ denote the Fourier transforms of the corresponding time-domain signals $y(t)$ and $x(t)$. In the presence of noise both at input and output, the logarithmic averaging procedure [11] is proposed to obtain an estimate of the FRF, which yields

$$G_{\log}(j\omega) = \left(\prod_{k=1}^{R} \frac{Y_{rk}(j\omega)}{X_{ek}(j\omega)} \right)^{1/R} \tag{2}$$

where R denotes the number of averaged measurements, and $X_e(j\omega)$ and $Y_r(j\omega)$ denote the Fourier transforms of $x_e(t)$ and $y_r(t)$.

2.1 Maximum-length binary sequence

Pseudo-random binary sequence (PRBS) $\{a_k\}$ is a maximum length binary sequence (MLBS) if, and only if, it satisfies a linear recurrence

$$a_k = \sum_{i=1}^{n} c_i a_{k-i} \ (\mathrm{mod}\ 2) \tag{3}$$

and has a period length of $P = 2^n - 1$, where c_i has a value of 0 or 1. The MLBS can be generated by an n-bit shift register with exclusive or (XOR) feedback. In practice, the values 0 and 1 generated by the shift register are mapped to -1 and +1 to produce a symmetrical MLBS with an average close to zero.

The MLBS-based signals have a number of properties that are useful for FRF measurements. One of the most important properties is that the periodic autocorrelation function (ACF) of the MLBS is approximately a periodic unit impulse sequence. In addition, the sequence has the lowest possible peak factor; that is, its energy is very high in relation to the signal's amplitude [11]. Another advantage of the signal is that it can be generated with a low-cost application, the output of which can only cope with a small number of signal levels. Furthermore, because the sequence is a periodic signal, the leakage in the frequency-response calculation can be fully avoided.

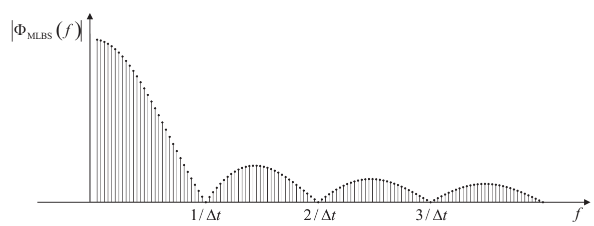

Figure 2: Shape of power spectrum of MLBS.

The power spectrum $|\Phi_{\mathrm{MLBS}}(f)|$ of the MLBS is defined as the Fourier transform of the sequence's ACF, and follows the $sinc^2$-function [11]. The power spectrum has an envelope and drops to zero at the sequence's generation frequency, as shown in Fig.2, where Δt denotes the sample interval of the sequence. Clearly, the generation frequency of the signal has to be selected so that the bandwidth of the sequence covers the frequency band where the system is to be identified. For more detailed design issues of the MLBS and other, alternative binary excitation sequences, see [13] and [14].

3 EXPERIMENTS

A schematic picture of the designed nanowire tensile test and electrical characterization system is shown in Fig. 3. The gray area presents an electrostatically actuated tensile device, which is placed under a high-resolution optical microscopy during the experiment. A nanowire is placed and welded into the tensile device. The nanohandling process and integration technology is fully described in [15]. After the integration, one end of the nanowire is attached to a movable component of a comb drive actuator, while the other end is attached to a microforce sensor beam which can evaluate the tensile force applied on the nanowire by measuring its tensile deformation. Three electrodes are prepared on the device. An I/V analyzer is connected to electrodes A and B which are connected to the two ends of the nanowire, while a DC supplier is connected to electrodes B and C which are attached to the movable combs and fixed combs of the actuator respectively.

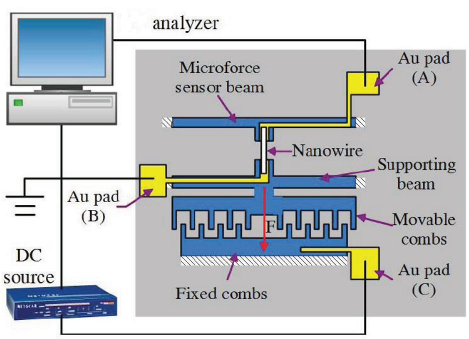

Figure 3: Conceptual diagram of the applied tensile test device with an attached nanowire.

The interface board communicating between the computer and the device under test is National Instruments USB-6251 measurement card (MC). The maximum sampling frequency of the card is 500 kHz per channel, and the maximum digital-to-analog converting frequency is 2.8 MHz. The measured data is digitized by a 16-bit analog-to-digital (A/D) converter. The measurement card is controlled by Matlab/Data Acquisition-toolbox.

Since the data acquisition card used was not directly suitable for measuring high impedances or small currents, a measurement amplifier was designed. The simplified block diagram of the amplifier is shown in Fig. 4. The MLBS excitation from the measurement card is first attenuated. This excitation voltage is then filtered with a second order 120 kHz filter in order to limit the rate of change and thus the current required to charge unknown capacitive impedances. The signal is then fed to a transimpedance amplifier - difference amplifier combination, which mirrors the excitation voltage to the unknown impedance while measuring current through it. The result is then filtered and amplified.

The amplifier uses two independent methods of input capacitance compensation, which can be used separately or together. The first method functions by driving the cable shield (or a special guard electrode) with excitation voltage, thus negating the effects of capacitance between input and shield. The second method works by feeding an adjustable amount of compensating charge to the amplifier input, thus compensating adjustable amount of stray capacitance between input and ground.

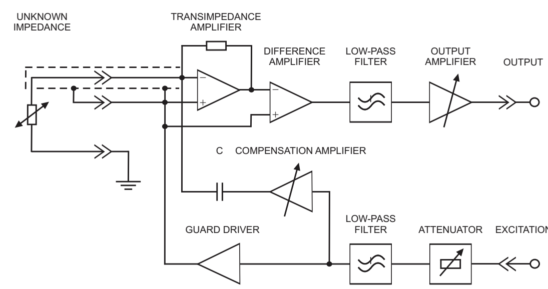

Figure 4: Simplified block diagram of the applied amplifier.

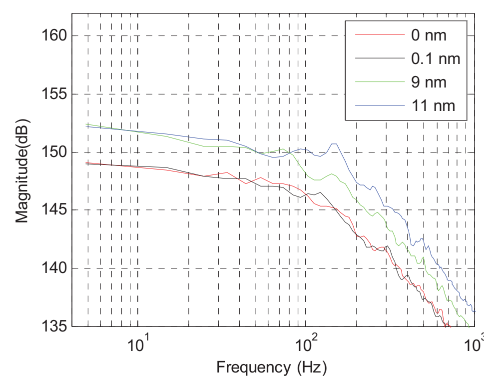

Figure 5: Measured frequency response of U/I of the attached nanowire with various stretching values.

The injected excitation was an 1023-bit-length MLBS with a generation frequency of 10 kHz. The amplitude was set to 100 mV. The excitation was injected with 100 periods and Eq. (2) was applied. The nanowire was streched between 0 nm and 11 nm, and the measurements were repeated every time. Fig. 5 shows the measured resistances with various stretching values of the nanowire. The figure clearly shows how the stretching affects the resistance. Fig. 6 gives a closer look of the resistances when the nanowire is not stretched and when it is stretched by 11 nm. The figures also show some frequency dependency on the resistance. The bandwidth of the current amplifier was approximately 120 Hz so the results beyond this frequency are not reliable.

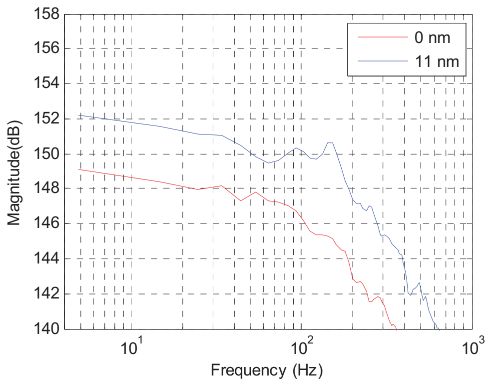

Figure 6: Measured frequency responses with stretching values of 0 nm and 11 nm.

4 CONCLUSION

An electrostatic actuating tensile device was applied and the resistive characteristics of a silicon nanowire were evaluated by means of the MLBS and Fourier techniques. The experiments showed that the nanowire resembles almost an ideal resistance within the bandwidth of the applied measurement devices, and shows remarkably change in the resistance as the strain is varied; higher stretching force yields higher value in resistance. The presented methods can efficiently be used to determine the electrical properties of nanostructures under varying mechanical stress, thus giving valuable information and performance characteristics of applied nanodevice.

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