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Control of polysilicon nanowires conductivity by angle-dependent ion implantation

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ABSTRACT

Boron doped polysilicon nanowire devices were fabricated using lithography-based top-down method. The devices, implanted by boron ions at different angles (0°,20°,30°,45°), exhibited significant dependence of electrical conductivity on incident implantation angle. Monte Carlo simulations of the dopant distribution, show that the projected range of boron implant increase with decreasing incident angle, in agreement with literature SRIM (Stopping and Range of Ion in Matter) reported data. The simulations and electrical measurements, show that geometrical shadowing reduce the device conductivity, while lower incident implantation angles increase it. This implies that Polysilicon Nanowires conductivity can be controlled by changing the implant angle, and this is beneficial for 'top = down' fabrication of SiNW sensors based on accumulation and depletion.

1. Introduction

Silicon nanowires (SiNWs) are attractive for future nanoelectronics, sensors and photonic and optoelectronic devices [1]. The functionality of semiconductor devices depends on the possibility of adjusting their electronic properties by the addition of dopants. These shallow-level impurities, such as B, P, As, Ga, Al, or Sb, tune the position of the Fermi level within the Si band-gap, such that the type and concentration of the majority charge carriers is defined by the dopant concentration [2]. In SiNW, determination of intentional doping profiles (both axially and radially), probing the unintentional dopants distribution and the characterization of electrical junctions are essential for understanding device performance [3].

NWs doping methods can be divided into two major groups: *in-situ* doping, in which the dopants are introduced into the system during growth and *ex-situ* doping where dopants are added after the growing stage. *In-situ* doping is achieved by changing the gas-phase precursor, namely by adding a doping precursor to the system (VLS growing) [4,5]. For example, the addition of phosphine (PH_3) precursor to the growth system produces an n-type NW, and the addition of diborane (B_2H_6) will produce a p-type NW. The control of dopants concentration is achieved by adjusting the gas ratio of precursors inside the reactor. Several works have shown that using this method of doping can lead to a highly non- uniform distribution of dopants along the nanowire as reported by Koren et al. in 2010 [2]. This non-uniformity is a consequence of different wire areas exposed to the gaseous dopant precursor for longer periods than other areas, because the bottom part of the wire is exposed to the precursor's atmosphere for longer time than its tip during the growth. Moreover, VLS method suffers from significant limitations: difficulty to assemble the wires in an electronic device and sensitivity to metal contamination from the catalysts [2].

Ex-situ doping are methods in which doping atoms are introduced to an already grown intrinsic, or otherwise doped, NWs. In 2008, Ho et al. introduced a novel method of *ex situ* doping called the monolayer doping (MLD) [5]. The method is based on two steps, the first is the formation of self-assembled monolayers of dopant containing molecules on the surface of the NW. This approach benefits from the well-defined and deterministic positioning of covalently attached monolayers. The samples are then capped with a SiO_2 layer to promote dopants drive-in into the semiconductor wire. In the second step, the reacted interface is exposed to rapid thermal annealing (RTA) which results in molecular dissociation and thermal diffusion of dopant atoms into the NW. Subsequently, the capping layer is removed by etching.

Another *ex-situ* doping method that is widely used in semiconductor fabrication is ion implantation. In this method, ions of the doping material (B, P, As for example) are accelerated in electric field and impacted into a solid. The equipment typically consists of an ion source, where ions of the desired element are produced, an accelerator, where the ions are electrostatically accelerated to a high energy, and a target chamber, where the ions impinge on a target, which is the material to be implanted (i.e. the process wafer). Ions energy, as well as the ion species and the target composition, determine the depth of penetration of the ions in the solid. Ion dose [ions/cm^2] is precisely controlled by beam current and implantation duration, will determine the total

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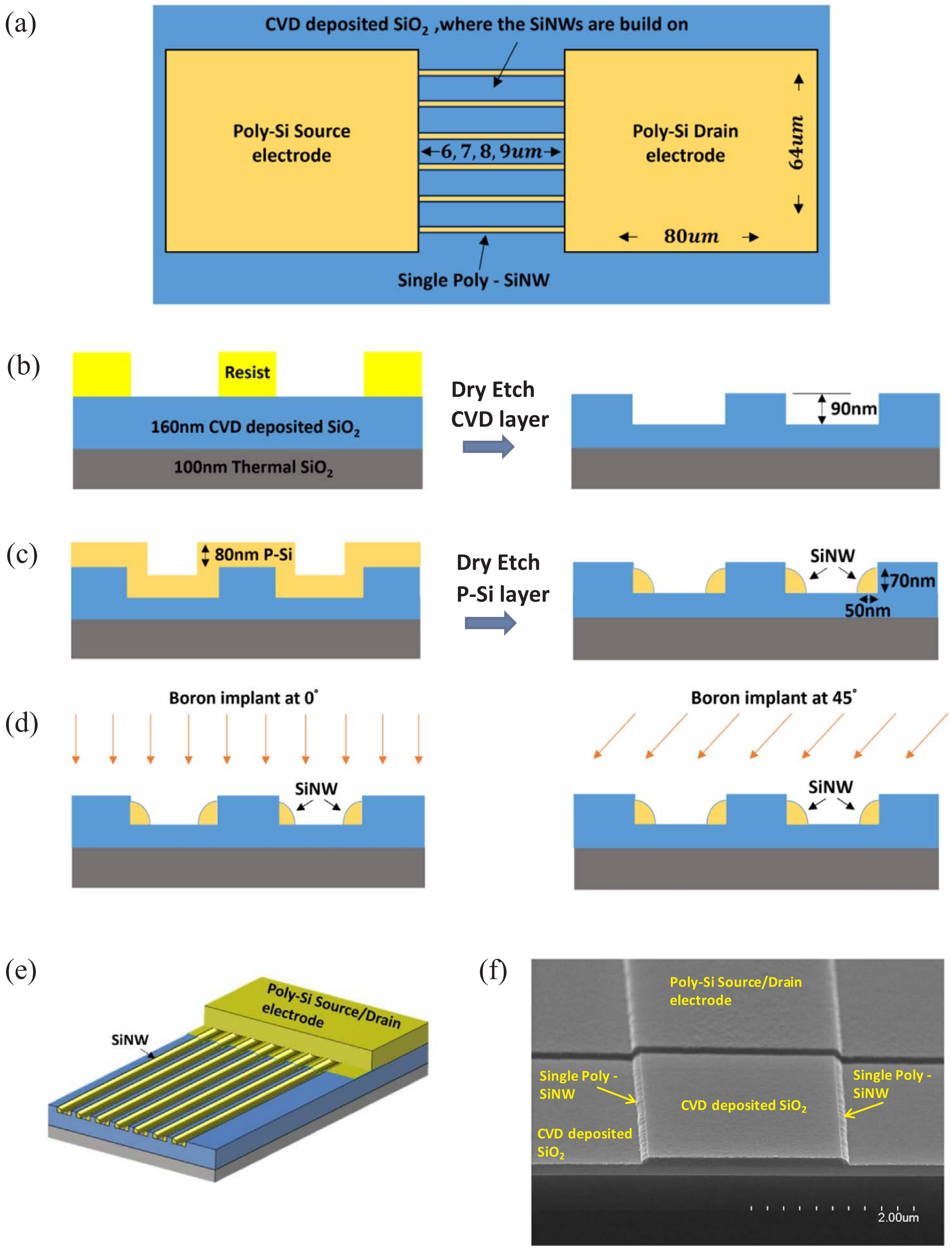

Fig. 1. Process flow illustration of the critical process steps concentrating on the SiNW formation area. (a) Top-View schematics of the device. Each device contains 50 SiNW (b) Oxide spacer formation. Source/drain areas are defined at the same time (c) Poly-silicon etch and nanowires formation. Source/drain areas are covered with poly-silicon and protected during nanowire etch formation (d) Ion implantation at 0° and at 45°. Wires implanted at 0°, 20°, 30° and 45°. Source and drain areas are perpendicular to the nanowires, hence, they do not appear in this illustration. (e) Illustration of a P-SiNW device. Only half a device is seen on this image. (f) SEM image showing two SiNWs connected to an electrode (either source or drain).

doping concentration in the implant process. The Ion implantation process usually create a damage to the target surface (depends on the energy, ion types and substrate), which can create a complete amorphization of target's surface. This fact is critical for SiNW electrical properties due to their small dimensions. A typical recovery is an annealing process which recovers the crystalline structure caused damaged by the implantation process. The final dopants depth and concentration is determined by the combination of the Ion implantation and annealing processes [6].

Common Si doping levels for device applications can range from 1×10^{15} [cm^{-3}] to 1×10^{20} [cm^{-3}] corresponding to a maximum atomic impurity concentration of 0.2% [12]. Hence, detecting dopant in Si nanowires requires extremely high sensitivity. Methods like KPFM (kelvin probe force microscopy) [2], SPCM (scanning photo current microscopy) [14] and APT (atom probe tomography) [16] are used for SiNW doping characterization. However, they are suffering from difficulties in measuring cross section doping compared to surface distributions and from challenges with sample preparation.

Monte Carlo simulators for cross section doping prediction, are based on SRIM (stopping and range of ion in matter) [17–19] and allow to predict ion distribution in nanowires [9]. Simulators are based on particles scattering path and energy lost when implant ion interact with a substrate. They use incident and substrate atomic mass, distance between incident and stationary particle, collision scattering angles and incident velocity for SRIM calculations.

The devices in this work were produced by top-down process which allows to fabricate the wires as part of a general device. Therefore, it allows direct measurement in 4 points probe test after production. The objective of this work is to determine dopant concentration and cross section distribution of boron implanted poly-silicon nanowires which doped at different angles. We have used the spacer trimming technique [1,7,13,15] in order to produce arrays of P-SiNW and boron doped them by ion implantation to function as electrical devices. SiNW doping was characterized by Monte Carlo simulations, and model to explain electrical measurements is presented.