229c Controlled Metal-Catalyzed Growth of Silicon Nanowires for Device Integration [Invited]

Shashank Sharma, Amir A. Yasseri, M. Saif Islam, Theodore I. Kamins, and R. Stanley Williams

Chemically synthesized semiconductor nanowires are expected to be of interest for a variety of electronic, optical, and optoelectronic device applications. Despite the rapid progress made in recent years in bulk synthesis of nanowires, a major challenge remains, that is, large-scale fabrication of novel, reliable, and robust nanowire-based devices. There exist two mainstream approaches to build nanowire-based electronic devices. One approach involves dispersing nanowires in an aligned or unaligned fashion on a substrate and subsequently making electrical contacts to the ends of the nanowires. This approach can yield valuable information about the device physics; however, it involves additional processing steps and it is unviable to yield a large number of robust and reliable devices.

This presentation focuses on an alternate approach that involves controlled chemical synthesis of nanowires and in which nanowires are grown "in-place" within an already existing device and electrical contacts are made during the nanowire growth, thus making possible integration of nanowires in large-area device arrays. As means of integrating nanowires by growing them in an existing device structure, a metal-catalyzed chemical vapor deposition (CVD) method will be discussed that addresses several key issues such as the nanowire growth orientation, location, selectivity, and thermal stability.

Nanometer-scale Ti-silicide islands and Au-Si eutectic droplets have been previously shown to catalyze the growth of silicon in one dimension to form free-standing nanowires by CVD. The nanowires typically grow epitaxially along the <111> crystallographic directions, therefore, perpendicular to {111}-oriented silicon surfaces. We have demonstrated lateral growth of Au- and Ti-catalyzed silicon nanowires from a vertical sidewall of a trench on a silicon-on-insulator (SOI) substrate ((011)-oriented silicon layer). Upon impinging on the other sidewall, the nanowires attach to this "opposing" sidewall, thus bridging across the trench and making strong mechanical connection. The nature of the connection at the impinging end will partially determine the electrical and mechanical behavior of the electronic device. We will discuss in detail current-voltage (I-V) measurements of Au-catalyzed silicon nanowires that were doped during the growth using diborane mixed with the $SiH_4/HCl/H_2$ ambient in the CVD reactor. The I-V dependence was observed to be linear, indicating good electrical contact formed in-situ between the nanowires and the electrodes. I-V measurements also indicated boron concentrations in thicker nanowires (diameter >100 nm) in the mid-10^{18} cm^{-3} range, corresponding to those observed for epitaxial silicon deposition on a plane silicon surface, with boron concentration increasing with increasing diborane partial pressure in the gas phase. Doped bridging nanowires discussed here that are grown on an SOI substrate can further be developed into effective sensors for species in gas or solution phase that cause a change in the electrical conductivity of the nanowires.

In addition to the growth orientation, a good control over the location of nanowire growth is also essential in enabling seamless integration of semiconductor nanowires in devices. In this presentation, we will demonstrate selective growth of Au- and Ti-catalyzed silicon nanowires on vertical silicon surfaces compared to horizontal silicon dioxide surfaces. In the case of Au-catalyzed nanowires, for a particular set of annealing conditions and nanowire growth conditions, there is a critical Au film thickness, below which we did not observe nanowire growth. We used angled evaporation of Au to utilize this observation to enable nanowire growth selectively on vertical surfaces. In the case of Ti-catalyzed nanowires, the desired selectivity was achieved by CVD of Ti using liquid $TiCl_4$ source.

A key observation in this work is the <111> growth direction of Au and Ti-catalyzed silicon nanowires that grow epitaxially on {111}-oriented silicon surfaces. As discussed here, nanowires can be grown laterally if the {111}-oriented silicon surfaces can be fabricated vertically. However, in order to develop a more generic nanowire integration approach for a variety of device layouts and to allow better process

flexibility, ability to grow nanowires in desired orientations (with or without the epitaxial registry with the substrate) with respect to the existing device layout will be crucial. In this paper, we will discuss possible approaches to grow nanowires in desired orientations that include exploring different catalyst materials and fabricating features on the substrates that aid nanowires to grow in a specific orientation.

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