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Attraction of semiconductor nanowires: An in situ observation

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Abstract

In situ deformation transmission electron microscopy was used to study the attraction behavior of GaAs semiconductor nanowires (NWs). The NWs demonstrated an interesting phenomenon of either head-to-head or body-to-body attraction at distances that depend on the NW diameters. The NWs with a diameter of ~25 nm attracted at a distance of ~25 nm, while large-diameter NWs of ~55 nm showed no obvious attraction. The underlying mechanism governing the attraction of the NWs is proposed and discussed with a mechanistic model. The diameter dependence on the NW attraction behavior is discussed. The finding provides an understanding of the Ampère force in nanostructured materials caused by an electron-beam-induced current while technologically it provides useful hints for designing NW-based devices according to the diameter-dependent attraction behavior of NWs.

Keywords: Attraction; GaAs nanowires; Ampère force; Diameter dependence; Electron-beam-induced current

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1. Introduction

One-dimensional (1-D) semiconductor nanostructures, including nanowires (NWs) and nanotubes, have attracted much attention because of their unique electrical, optical, mechanical and thermal properties and their potential in a wide variety of nanoelectronic, optoelectronic and nanoelectromechanical applications [1–6]. The interest in III–V NWs stems from their suitability for exploring fundamental physical phenomena at the nanoscale as well as their promising applications in optoelectronic devices [7–16]. When NWs are grown in a high density, attraction and bundling of NWs under external stimuli become a significant problem, which could affect the functionality and reliability of NW-based devices. Therefore, a fundamental understanding of the NW attraction phenomenon is essential.

Attraction behavior has been observed in ZnO NWs with a wurtzite (WZ) structure. This phenomenon was explained using either a metal–semiconductor junction model or a polarized surface model [17–20]. These mechanisms could not explain the complex situation of the NW attraction at different positions of the NWs well. Thus, further exploration on the attraction of semiconductor NWs is necessary. From a practical point of view, applications of II–VI, III–V and group IV NWs as optoelectronics are generally under an external stimulus (for example, solar light), while fundamental structural investigations of these NWs are conducted in electron microscopes as the electron beam being a stimulus source.

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Electron–hole (e–h) pairs will be generated within semiconductor NWs under those stimuli and then how the NWs behave is still a fundamental physical problem. With the recent advancement of in situ deformation transmission electron microscopy (TEM) [21–25], it is now possible to perform unambiguous investigations on each individual NW and would therefore clarify the NW attraction mechanism to present an in-depth understanding of NW interactions.

In this paper, the attraction phenomenon in GaAs semiconductor NWs was investigated using an in situ deformation TEM technique. We demonstrate that the GaAs NWs attract each other in the form of either head-to-head or body-to-body contact within distances that depend on the diameters of the NWs. The underlying mechanism of the phenomenon and the effect of NW diameter on the attraction distances will be discussed.

2. Experimental

Single crystal GaAs NWs were epitaxially grown on GaAs $(1\,1\,1)_B$ substrates using Au nanoparticles as the catalyst with trimethylgallium and AsH_3 as the precursors by metal–organic chemical vapor deposition. The $(1\,1\,1)_B$ orientation was used to enable epitaxial vertical growth of the NWs on the substrates since the $(1\,1\,1)_B$ surface has the lowest surface energy. Ultrahigh-purity hydrogen was used as the carrier gas. Details on the growth of GaAs NWs have been reported elsewhere [26,27]. The morphology of the GaAs NWs was characterized by scanning electron microscopy (SEM, Zeiss Auriga). Samples consisting of numerous GaAs NWs free-standing on the substrate were attached on a mount, which was held in a Hysitron PicoIndenter (PI 95) holder. In situ TEM observation of the attraction of the NWs was carried out using the PicoIndenter with a flat diamond punch in a JEOL JEM-2100 TEM. The attraction process was recorded by TEM images and real-time video at the speed of 30 frames s^{-1}. After the in situ experiments, atomic resolution structural characterization of the GaAs NWs was conducted using a JEOL JEM-3000F TEM.

3. Results

In order to in situ investigate unambiguously the attraction behavior of GaAs NWs, the NWs were deliberately grown in a low density. Fig. 1a presents an SEM micrograph of the GaAs NWs. All NWs have uniform morphology and are aligned vertically to the substrate. A typical NW is magnified in Fig. 1b, which shows a hexagonal geometry. Fig. 1c shows a typical TEM image of a GaAs NW with a diameter of ∼25 nm. The atomic resolution image of the GaAs NW obtained from an area marked with A is presented in Fig. 1d. It has a periodical stacking sequence of “AaBbAaBb…”. The inset shows a corresponding fast Fourier transformation (FFT) pattern, demonstrating a wurtzite structure. The NWs grew along the $[0\,0\,0\,1]$ direction as confirmed by TEM. Note that an amorphous oxide layer with a thickness of ∼2 nm is seen on the surface of each NW, which was formed when the NW was exposed to air upon unloading from the growth chamber.

Fig. 2a–d shows a series of in situ deformation TEM images extracted from Movie 1 in the Supplementary materials, revealing the attracting and detaching processes between two broken segments of a GaAs NW. A single GaAs NW was initially fractured into two separate parts by in situ compression testing, where one originally grew on the substrate and the other was attached on the diamond punch (Fig. 2a). When moving the punch horizontally to the right, the lower NW segment attached to the diamond punch gradually approached the upper NW segment on the substrate. At a distance of ∼25 nm, which was measured between the sidewall surfaces of the two NW segments (two arrows in Fig. 2a), they suddenly attracted each other and came in contact at the edges (Fig. 2b). In order to check the extent of the attraction, the punch was moved to the left, as shown in Fig. 2c. The upper NW segment bent gradually (the dotted line indicates the initial position of the NW) as the punch moved to the left. When the horizontal displacement, x, reached ∼25 nm, the two segments suddenly detached from each other and returned to their original states (Fig. 2d).

The attraction phenomenon was also observed between two different GaAs NWs. Fig. 2e–h presents several snapshot images extracted from Movie 2 in the Supplementary materials. Fig. 2e shows a complete NW with an Au nanoparticle (the dark contrast point at the tip of the NW) attached to the substrate and another NW attached to the punch. Note that the NW on the punch came from a previously fractured NW. These two NWs started to attract each other at a distance of ∼25 nm. It should be pointed out that they showed a body contact with each other, as seen in Fig. 2f. The same experimental procedure as that shown in the Movie 1 was performed, and the two NWs began to separate when the maximum horizontal displacement also reached ∼25 nm (Fig. 2g). These NWs reverted back to their original positions, as shown in Fig. 2h after separation.

III–V semiconductors like GaAs also possess a cubic zinc blende (ZB) structure that has less polarity than the WZ counterpart, making it possible to explore the effect of polarity on the attraction phenomenon. Fig. 3a shows the typical high-resolution TEM image of a GaAs NW and the cubic ZB nature of the NW is confirmed by the corresponding FFT pattern shown in the inset [28]. A series of in situ deformation TEM images (Fig. 3b–e) demonstrates the attraction behavior of the ZB GaAs NW as similar to the description in Fig. 2. Note that the attraction behavior of the ZB NW is similar to that observed in the WZ case, which also occurs at an attraction distance of ∼25 nm.

4. Discussion

Obviously, van der Waals forces are not responsible for the attraction behavior since the attraction comes into