The Role of Collisions in Aligned Nanowire Growth

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Motivation—The epitaxial growth of vertical nanowire arrays with controlled properties is of interest for reasons of density, uniformity, anisotropy, coupled interactions, and device integration. However, a population of tilted, non-vertical nanowires is often inevitable due to competition from nanowires with different growth directions (including symmetrically equivalent directions within the family).

Accomplishment—We report here that collisions between tilted and vertical nanowires during growth can have a dramatic impact on the final alignment of nanowire arrays. We previously demonstrated the epitaxial growth of dense, highly aligned arrays of single crystalline, vertical GaN nanowires on unpatterned r-plane $(1\bar{1}02)$ sapphire substrates via Ni-catalyzed metal-organic chemical vapor deposition (MOCVD). Scanning electron microscope (SEM) and transmission electron microscopy (TEM) analysis indicate that the nanowires share a common $[11\bar{2}0]$ growth direction and have aligned facets.

An investigation of the initial growth process indicates that, in addition to vertically aligned nanowires, a significant fraction of tilted nanowires also nucleate, the density of which sharply decreases with growth time. Thus, the vertically aligned growth is not dominant initially but becomes so as the growth proceeds. Interestingly, we were able to observe collisions between tilted and vertical nanowires experimentally during the initial growth period, as shown in Fig. 1. We attribute this decay in the density of tilted nanowires during growth to these collisions with vertical nanowires, which are observed to terminate the growth of tilted nanowires but not vertical nanowires.

Based on this collision mechanism, we created a Monte Carlo model to simulate the decrease in the density of non-terminated tilted nanowires due to collisions with vertical nanowires. By normalizing the distribution of minimum collision lengths for a tilted nanowire growing in a field of vertical nanowires obtained after 2000 simulations, a decay curve can be plotted to show the percentage drop in non-terminated tilted nanowire density versus nanowire length. Figure 2 shows the tilted nanowire decay curves simulated for nanowire array densities from 0.5 μm^{-2} to 80 μm^{-2}. It is seen that the vertical nanowire density has a very large effect on the collision (decay) rate. At a vertical nanowire density of 1 μm^{-2}, the model predicts that approximately 90 percent of tilted nanowires are terminated by the time they reach ~5.27 μm in length, whereas at a higher density of 80 μm^{-2}, 90 percent of tilted nanowires are terminated by only ~0.25 μm in length. Thus, dense nanowire arrays are especially effective at rapidly filtering out the growth of tilted nanowires. However, the model shows that the effect of collisions is significant even at lower densities.

Significance—We have found that nanowire collisions play a critical role in the evolution of aligned, vertical epitaxial nanowire growth by terminating the growth of tilted nanowires, as seen for the case of epitaxial GaN growth on r-plane sapphire. A Monte Carlo model developed to simulate the collision process shows that at high nanowire densities, these collisions become a highly effective mechanism for filtering out the growth of titled nanowires, allowing vertical nanowire growth to dominate.

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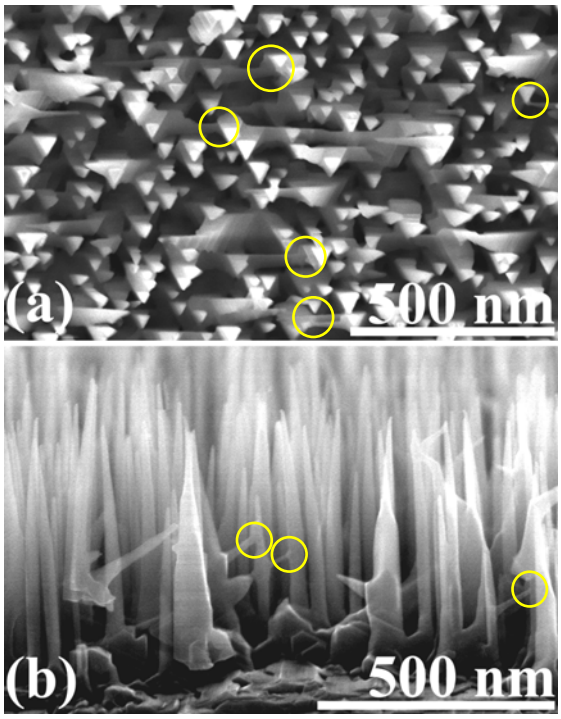

Figure 1. (a) Plan-view and (b) cross-sectional view SEM images of aligned, vertical GaN nanowires at 60 s growth. Vertically aligned nanowires appear as triangles with aligned facets in plan-view. Both plan-view and cross-section images capture collisions between tilted nanowires and vertically aligned nanowires (indicated by circles), which terminates further tilted nanowire growth.

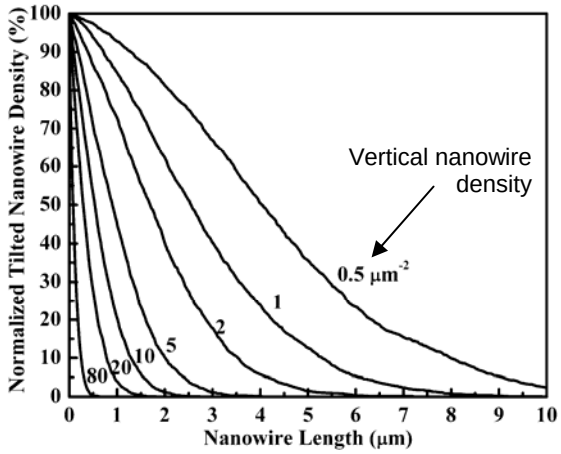

Figure 2. A Monte Carlo model shows the decrease of the non-terminated tilted nanowire density as a function of the tilted nanowire length at varying vertical nanowire densities. A high vertical nanowire density, e.g., 80 μm^{-2}, causes a rapid decrease in the non-terminated tilted nanowire density due to a high nanowire collision rate.