Aerotaxy: an efficient aerosol-based method for growth of device quality semiconductor nanowires

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Semiconductor nanowires, in particular in the III–V materials systems show great promise for applications in many areas, such as solar cells [1], light emitting diodes [2], and high-speed electronics [3]. The advantages of nanowires vary for the different applications; in solar cells, the wires act as antennæ, concentrating the light, which results in an absorption close to that of a thin film using only a fraction of the expensive III–V materials [1].

Ever since the first studies [4], III–V nanowires have most often been grown with MOCVD, although vacuum-based methods are also common. For high-end applications such as microelectronics, the cost of epitaxial growth is not prohibitive, whereas wafer-based epitaxy does not seem to be a viable route for creating thousands of square kilometers of solar panels. Fortunately, for many applications there is no need for epitaxy's high level of control in terms of individual wire position or very precise dimensions.

Aerotaxy is a new method for nanowire growth, under development in Lund since 2010 [5], based on a combination of nanowire growth and aerosol materials synthesis [6]. In Aerotaxy, size-selected seed particles (typically Au) are generated by evaporation, condensation, sintering, and size selection in a differential mobility analyzer. The particles are led to the cylindrical reactor chamber, where MOCVD precursors (typically trimethylgallium and arsine) are added, together with dopants. See Figure 1 for a schematic of the process.

The aerosol spends approximately 5 seconds in the growth reactor, during which time the seed particles grow into nanowires of 1–4 µm in length, depending on conditions. This growth rate on the order of 1 µm/s is roughly 100 times larger than that in MOCVD, and this is one reason why Aerotaxy is a more efficient method for growing nanowires. Being a continuous process, Aerotaxy is inherently more amenable to up-scaling as compared to batch-based MOCVD. Figure 2 shows typical resulting wires, illustrating the control in length and width.

The growth reactor is designed as a modular stack, allowing injection of different precursors and dopants at different positions. This allows the formation of *pn* junctions and heterostructures, with the important difference (as compared to MOCVD) that the switching take place in space and not in time. Naturally, the control and flexibility in Aerotaxy is not as great as that in MOCVD, since each different section requires a reactor module. Materials grown with Aerotaxy so far include *n*- and *p*-doped GaAs; $GaAs_{1-x}P_x$ [7], see Figure 2; and *pn*-junctions in GaAs.

[1] J. Wallentin, N. Anttu, D. Asoli, M. Huffman, I. Åberg, M. H. Magnusson *et al.*, Science 339 (2013) 1057-1060
[2] B. Monemar, B. J. Ohlsson, N. F. Gardner, and L. Samuelson, Semicond. Semimet. 94 (2016) 227-271
[3] S. Johansson, E. Memisevic, L.-E. Wernersson, and E. Lind, IEEE Eletr. Dev. Lett. 35 (2014) 518-520
[4] M. Yazawa, M. Koguchi, and K. Hiruma, Appl. Phys. Lett. 58 (1991) 1080-1082
[5] M. Heurlin, M. H. Magnusson, D. Lindgren, M. Ek, L. R. Wallenberg *et al.*, Nature 492 (2012) 90-94
[6] M. H. Magnusson, B. J. Ohlsson, M. T. Björk, K. A. Dick, *et al.*, Front. Phys. 9 (2014) 398-418
[7] W. Metaferia, A. R. Persson, K. Mergenthaler, F.F Yang, W. Zhang *et al.*, Nano Lett. 16 (2016) 5701-5707

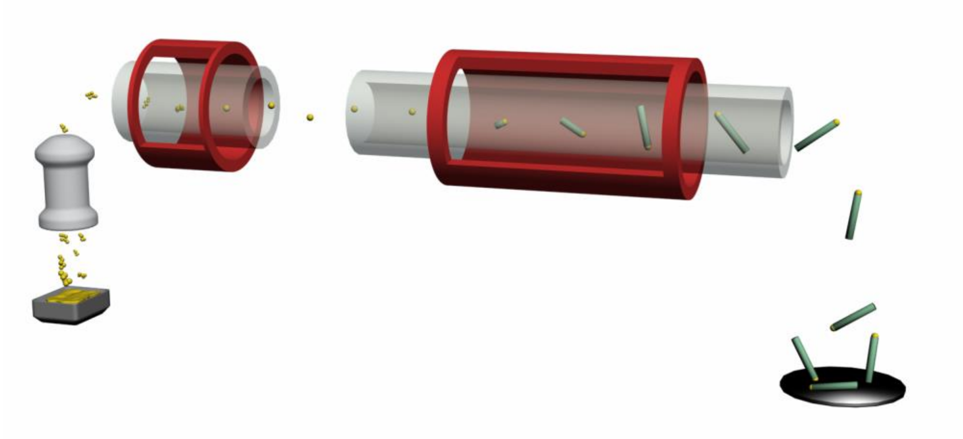

Figure 1. Principle of nanowire growth by aerotaxy, going from left to right: Au is evaporated, forming an aerosol of Au particles, which are size-selected, sintered, mixed with AsH_3 and TMGa in a tube furnace, and collected on a substrate. In this continuous flow process, 10^9 particles per second grow into nanowires at a rate of around 1 μm/s [5].

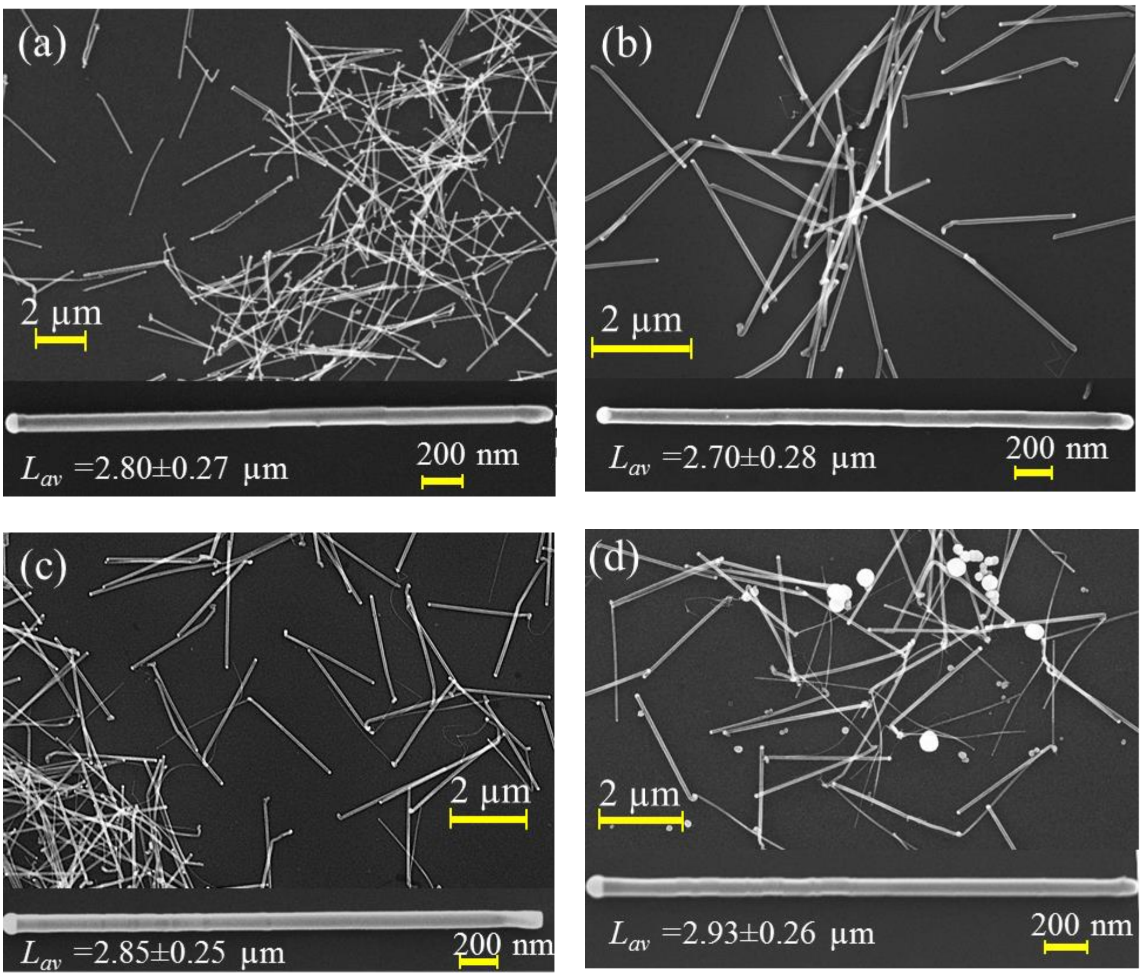

Figure 2. SEM images of $GaAs_{(1-x)}P_x$ NWs grown at 550 °C and with x = (a) 0.00 [pure GaAs] (b) 0.25, (c) 0.50 and (d) 0.75. L_{av} represents the average NW length with the ± fractions representing one standard deviation based on 30 measured wires. The lower panel in each image is a representative single NW image [7].