

# Gallium nitride nanowires achieve crystalline perfection

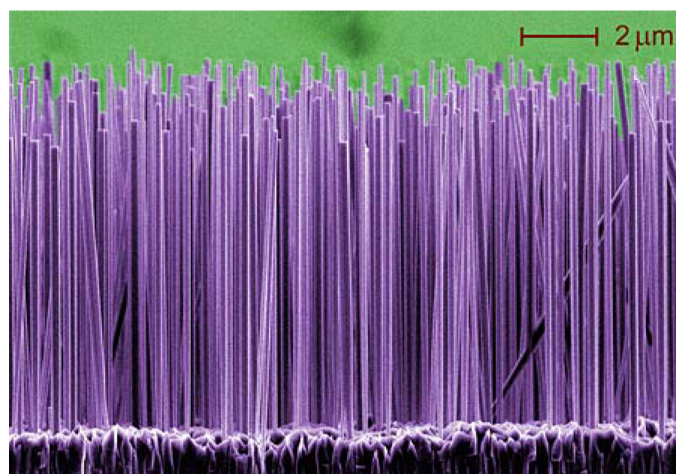
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*A new method of growing a common semiconductor provides an avenue for fabricating perfect crystals in a form that takes advantage of their unique optical, electrical, and mechanical properties.*

Gallium nitride (GaN) is a semiconductor material widely used for lighting and power transistor applications because of its abilities to emit UV and visible light and to tolerate high temperatures and voltages. In commercial production of these devices, GaN is deposited on wafers made of different materials because large GaN wafers cannot yet be economically grown, in contrast to mature silicon wafer technology. These conventionally grown GaN films suffer from high defect densities arising from the merging of the crystal structure of the film with that of the wafer. The defects lead to weaker light emission, electrical signal noise, and early device failure.

A number of crystal-growth ‘tricks’ reduce defect densities in ordinary GaN films or allow devices to be less sensitive to imperfections. These methods have improved device performance incrementally over the last two decades. Complete elimination of defects requires a more radical approach. Nanowire growth using a specific deposition method, molecular beam epitaxy (MBE), can achieve near-perfect crystal structure while retaining the semiconductor properties needed to make useful devices, as reviewed elsewhere.<sup>1</sup>

MBE-type GaN nanowires naturally grow in one direction (see Figure 1) due to thermodynamic driving forces on the surface energies of the crystal planes and sticking coefficients for incoming atoms.<sup>2</sup> The diameter of these nanowires is typically 150–300nm, but we have observed them outside this range. The crystalline perfection arises from the slow growth rate near thermal equilibrium, allowing defects generated at the root of the nanowire to quickly move to the sidewalls, where they terminate. The remaining growth is then free of both strain and defects, despite the large crystal mismatch between GaN and the silicon substrate. Chemical impurities are minimized by the high-purity starting materials and vacuum environment offered by MBE and the absence of catalyst particles.

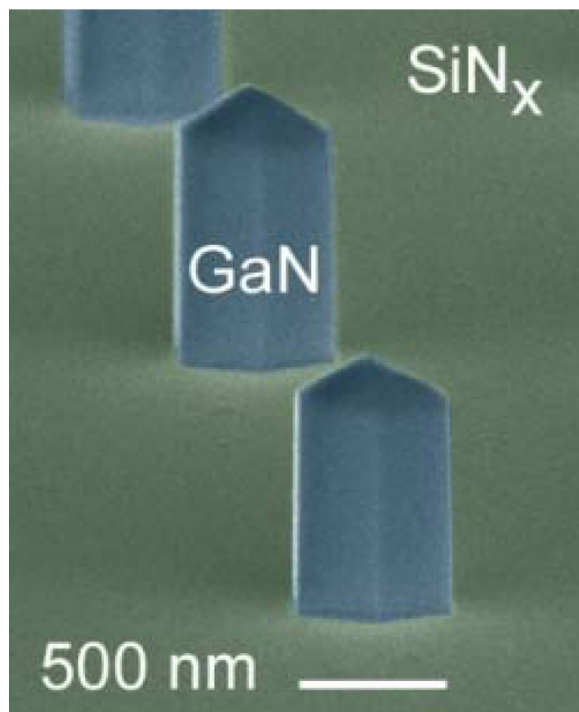


**Figure 1.** Gallium nitride (GaN) nanowires grown by molecular beam epitaxy with random nucleation. (Photo by Lorelle Mansfield, National Institute of Standards and Technology.)

We have demonstrated the crystalline perfection of the nanowires in a number of ways. First, the optical emission spectra of the nanowires and long photoluminescence lifetime show that impurities and defects are below the sensitive detection limit for these methods.<sup>3</sup> Single GaN nanowires will lase when optically pumped at moderate thresholds.<sup>4</sup> The primary loss mechanism for photogenerated carriers at room temperature is surface recombination, although the exact nature of the surface states is still under investigation.

We examined these GaN nanowires using transmission electron microscopy (TEM) and found them to be defect-free except when nanowires merge during growth. Because subjecting a single nanowire to different TEM diffraction conditions to detect all important defect types is time-consuming, we only test a small fraction of nanowires this way. Methods such as evidence from optical spectroscopy are more compelling as statistical measures of low defect density. Other indications

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**Figure 2.** Selective epitaxy of GaN nanowires through a silicon nitride ( $\text{SiN}_x$ ) mask.

of high crystalline quality in nanowires are their low background charge-carrier concentrations and their unusually high mechanical quality factors ( $Q$  over 50,000),<sup>5</sup> both of which have been shown for large sample sets.

The nanowires are readily fabricated into field-effect transistors that show excellent on-off current ratios and near-ideal switching energy.<sup>6</sup> Although p-type doping and contacting remain a challenge for nanowires (and, to a lesser extent, for thin films), arrays of GaN nanowires with InGaN (indium gallium nitride) quantum wells readily emit light.<sup>7</sup> This device work has shown that the large surface-to-volume ratio for nanowires requires special measurement techniques (still under development) and new processing schemes to fully take advantage of the intrinsic high quality of the material. The high surface-to-volume ratio can enhance nanowire performance as sensors, either for change in mass<sup>8</sup> or for the change in surface charge when species bind on the surface.<sup>9</sup>

Practical device manufacturing will require greater control of nanowire placement and dimensions than can be achieved with random nucleation. We have focused recently on developing methods of selectively nucleating GaN nanowires in openings in silicon nitride masks (see Figure 2). Under a restricted range

of growth conditions, the nanowires nucleate only in the openings and also are limited in diameter to a size just slightly larger than the opening.<sup>10</sup>

GaN nanowires grown by MBE thus offer material of higher quality for manufacturing light-emitting diodes and high-power transistors than can be attained with conventional growth approaches. The remaining challenges for us are to measure and control charge-carrier concentration with greater accuracy and to reduce surface recombination and environmental effects.

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