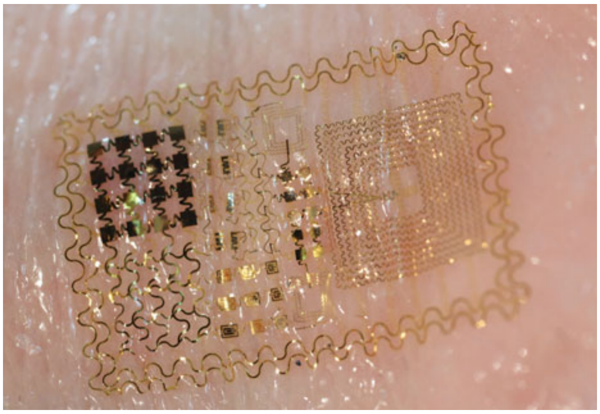
Bio Focus

Filamentary serpentine layout enables epidermal electronic "smart skin"

"Narrow, wavy, and thin"—that's how John Rogers of the University of Illinois at Urbana-Champaign describes the new "epidermal electronics" that he and his co-workers have developed for both monitoring electrical signals from the heart, brain, and muscles, and for stimulating muscles by supplying electrical signals. As reported in the August 12 issue of *Science* (DOI: 10.1126/science.1206157; p. 838), they have fabricated elastomeric patches containing open, spiderweb layouts of electrical circuits that have elastic modulus and bending properties very close to that of human skin. This will make them easy to wear and potentially useful, for example, in sleep studies, neonatal care, and rehabilitation applications.

The key to the flexibility and stretchability of the design is the "wavy" nature of the electronic circuits. This is known more technically as a "filamentary serpentine" layout, which consists of components with many large loops instead of shorter, linear circuit paths.

"If you look at the designs that best match the properties of skin in our work, they involve the *entire circuit* consisting of this filamentary serpentine shape," Rogers said. "So not only the interconnect wires but the devices themselves—the silicon itself, including transistors and the other device components—have this serpentine geometry." Quantitative mechanics modeling was used to determine the optimal thickness of the filaments and the loop geometry for the best skin matching.



The electronics are mounted directly to the skin, with no need for wires, conductive gel, or pins. They bend, stretch, and deform with the same mechanical properties of skin, granting the wearer comfort and freedom of movement. *Photo courtesy:* John Rogers.

The result is an elastomeric patch less than 7 µm thick containing an antenna light-emitting diode, a wireless power coil, radio-frequency coils and diodes, a temperature sensor, and electroencephalogram, electrocardiogram, and electromyogram sensors to monitor the brain, heart, and muscle signals, respectively. The circuit is attached to the skin by van der Waals forces only, so no adhesive is needed; the van der Waals forces are sufficient to maintain conformal contact with the skin, withstanding normal body movements over periods of hours without cracking or delamination. The researchers have also experimented with commercially available temporary transfer tattoos that could conceal the circuitry and provide greater adhesion if necessary.

This technology is an outgrowth of the macroscale stretchable electronics that Rogers's group and others have been investigating. Earlier versions were just too thick (a few mm to 1 cm), with elastic moduli a few orders of magnitude too high to match human skin.

"We've extended some of those design concepts that we and others have been exploring in stretchable electronics to an extreme, in terms of design, filamentary shape, thinness, and modulus-matched substrate to enable this epidermal format," Rogers said. "We view it as a different class of technology for that reason, but it has historical origins in flexible and, more recently, stretchable forms of electronics."

Tim Palucka

Nano Focus

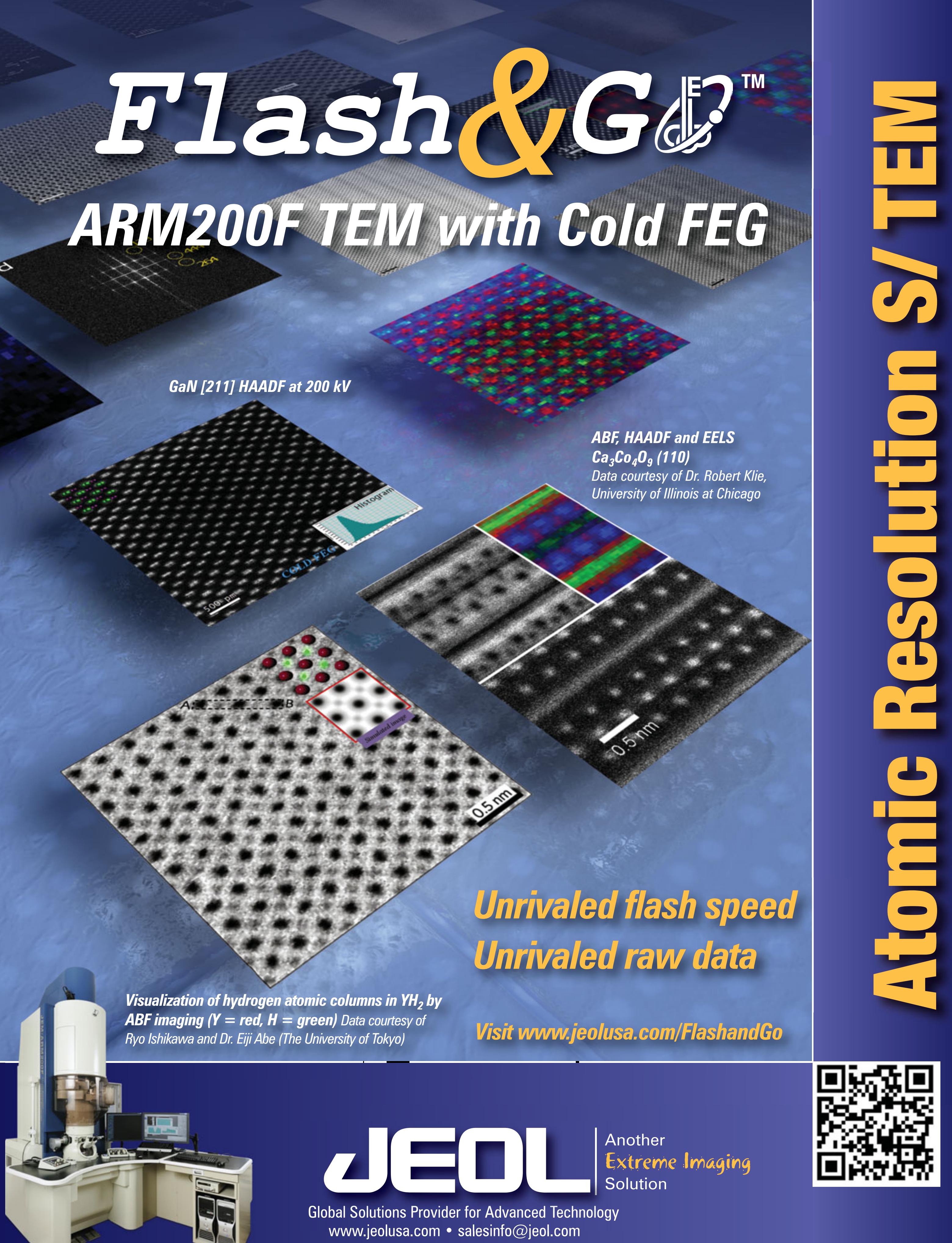
Millimeter-long GaN nanowires grow horizontally on sapphire substrate

Most nanowires are grown standing up, rising vertically from a substrate to reach heights in the range of tens of micrometers. They typically require post-fabrication processing to form aligned arrays of nanowires suitable for use in an electronic or optical device. Attempts to grow nanowires horizontally on a surface have had some success, but the resulting nanowires were still in the micrometer-length range, with limited control over their crystallographic orientation. Now, researchers at the Weizmann Institute of Science in Israel, led by Ernesto Joselevich, have reported in the August 19 issue of *Science* (DOI: 10.1126/science.1208455; p. 1003) the development of a process for producing *millimeter-long* GaN nanowires by guided growth on various crystallographic planes of a sapphire surface. The process allows the researchers to grow "very long and perfectly aligned horizontal nanowires with exquisite control of their crystallographic orientation," according to Joselevich.

The research team, which included graduate student David Tsivion, postdoctoral fellow Mark Schvartzman, and staff scientists Ronit Popovitz-Biro and Palle von Huth, used chemical vapor deposition of GaN on eight different sapphire planes seeded with Ni catalysts to achieve these results.

Analysis of the nanowires produced on these various planes revealed that those formed on surface steps and grooves were better aligned than those formed on a smooth plane. For instance, on a well-cut, smooth sapphire *c*-plane,

https://doi.org/10.1557/mrs.2011.244 Published online by Cambridge University Press

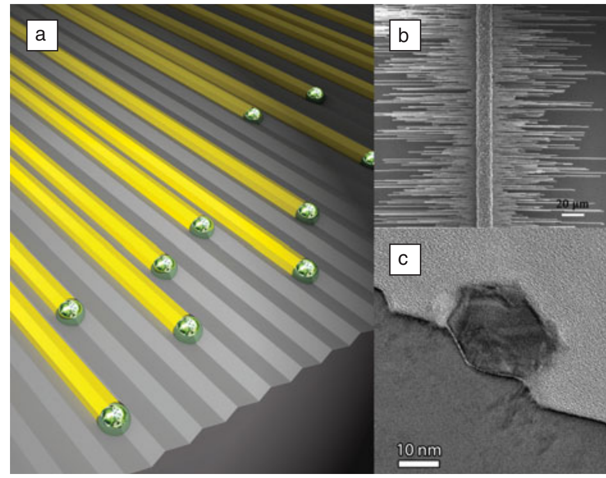

Flash&Go™
ARM200F TEM with Cold FEG
Atomic Resolution S/ TEM
GaN [211] HAADF at 200 kV
Histogram
COLD FEG
500 pm
ABF, HAADF and EELS
Ca3Co4O9 (110)
Data courtesy of Dr. Robert Klie, University of Illinois at Chicago
0.5 nm
A
B
Simulated image
0.5 nm
Unrivaled flash speed
Unrivaled raw data
Visualization of hydrogen atomic columns in YH2 by ABF imaging (Y = red, H = green) Data courtesy of Ryo Ishikawa and Dr. Eiji Abe (The University of Tokyo)
Visit www.jeolusa.com/FlashandGo
JEOL
Another Extreme Imaging Solution
Global Solutions Provider for Advanced Technology
www.jeolusa.com • salesinfo@jeol.com
978-535-5900

nanowires grew in random triangular patterns following six isomorphic directions. However, on a 2° miscut *c*-plane, the nanowires grew along only two directions, forming parallel arrays.

"We found that when the substrate is cut in a slightly tilted or unstable plane," Joselevich said, "the surface wrinkled up upon heating, and the tiny steps and grooves that formed on it made the alignment of the nanowires much better than on a smooth surface." Or, as the researchers reported in their article, "graphoepitaxy overrules epitaxy."

The researchers report that their GaN nanowires have few defects and that they exhibit excellent optical and electronic properties, which makes them potential candidates for nanoscale high-power circuits, light-emitting diodes, lasers, photovoltaic cells, photodetectors, and radio-frequency, photonic, and nonlinear optical devices. The relative absence of defects is atypical for semiconductors grown on a substrate, because stresses usually develop that produce defects.

"We think this is because, unlike a two-dimensional film, which usually gets stressed, a nanowire can relax by shrinking or swelling sidewise, making the system much more tolerant to mismatch than one is used to seeing in continuous two-dimensional films," Joselevich said. "This is a new one-dimensional nanoscale effect, which, together with the effect of graphoepitaxy, somehow changes the paradigm not only in the new field of nanowires, but also in the well-established fields of epitaxy and thin films."



(a) Illustration of nanowires growing along nanogrooves; (b) top view of the nanowires by scanning electron microscopy; and (c) cross-section view of a nanowire along a V-shaped nanogroove by transmission electron microscopy. *Image credit*: Ernesto Joselevich.

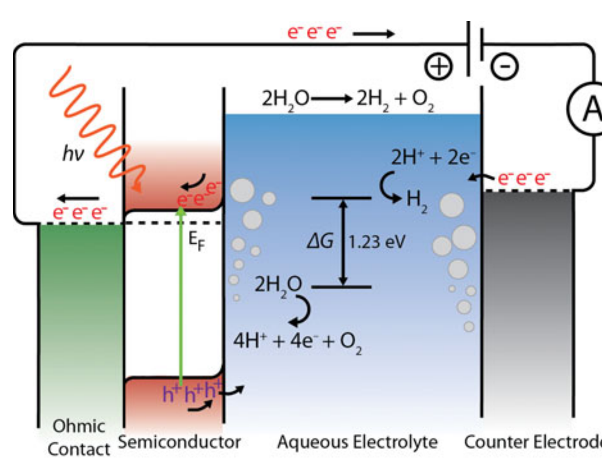
Tim Palucka

Energy Focus

Surface plasmons used to enhance solar-to-fuel energy conversion

Efforts to develop technologies for solar water splitting based on inexpensive, earth-abundant materials date back to the 1970s. Efficiencies of developed systems, however, remain low. One source of this inefficiency is the mismatch between the length scales of the key events; photon absorption occurs up to a few microns, while electron-carrier extraction is limited to several tens of nanometers. Photoexcited carriers are therefore generated too far from a reactive surface, and recombine before they can be converted to fuel. One general approach used to overcome this problem is the design of structured materials where the photon propagation and charge-transport directions are orthogonal to each other. Recently, I. Thomann and B.A. Pinaud from Stanford University and their colleagues showed that plasmonic resonances from metallic nanospheres can be combined with multilayer interference effects to better manage photons for more efficient solar conversion.

Collective electron oscillations in metallic nanoparticles are termed surface plasmons, and their resonance frequencies can be tuned from UV to near IR by changing the nanoparticle size, shape, and dielectric environment. As reported in the August 10 issue of *Nano Letters* (DOI: 10.1021/nl201908s; p. 3440), the research team employed the existing knowledge-base of plasmon-enhanced photovoltaics to demonstrate that plasmonics can enhance solar energy conversion to fuels. The researchers used a typical solar cell comprising an iron-oxide (α-Fe_2O_3) photoelectrode to measure wavelength-dependent photocurrents and therefore to determine the



This schematic of the band diagram shows the semiconducting electrode absorbing sunlight while in contact with an aqueous electrolyte solution in which photogenerated holes cause O_2 and electrons to be generated. The electrons are transported to a counter electrode where they react to produce H_2 and close the circuit. The researchers used α-Fe_2O_3 together with metallic nanoparticles as the semiconducting electrode, and measured the photogenerated current as a function of illumination wavelength. Reproduced with permission from *Nano Lett.* (DOI: 10.1021/nl201908s; p. 3440). © 2011 American Chemical Society.

https://doi.org/10.1557/mrs.2011.244 Published online by Cambridge University Press