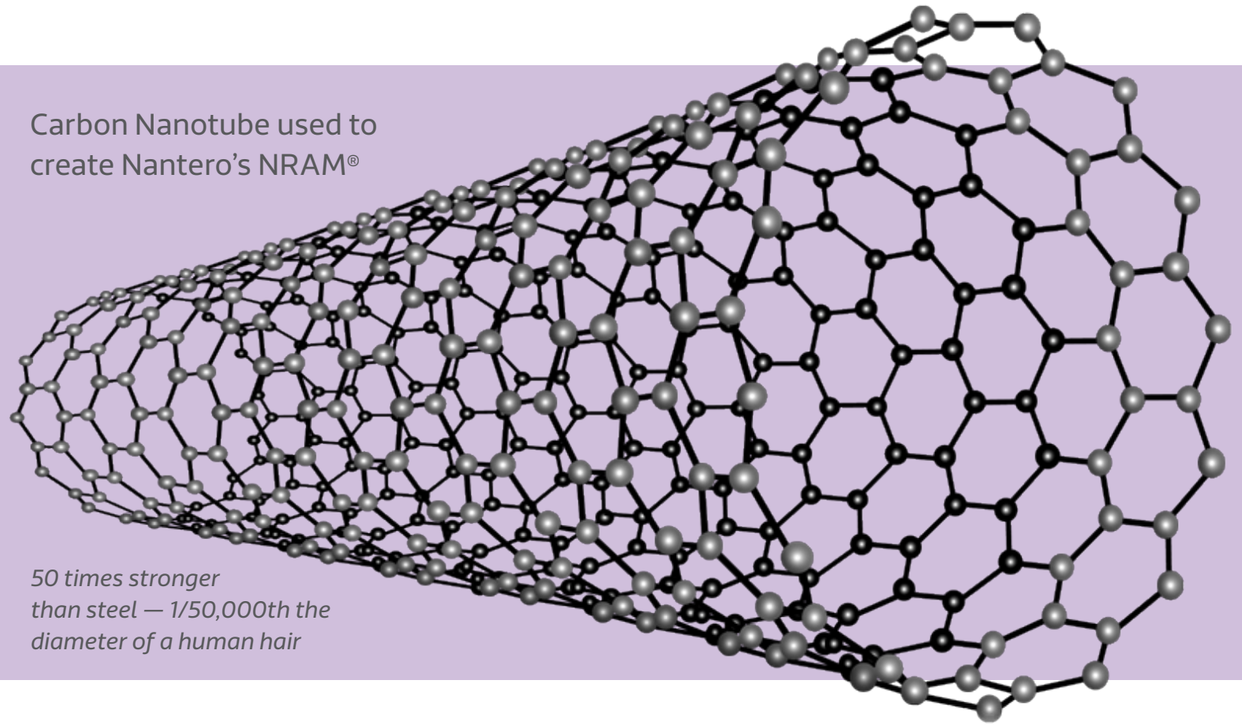
NRAM from Nantero Utilizes

CARBON NANOTUBES

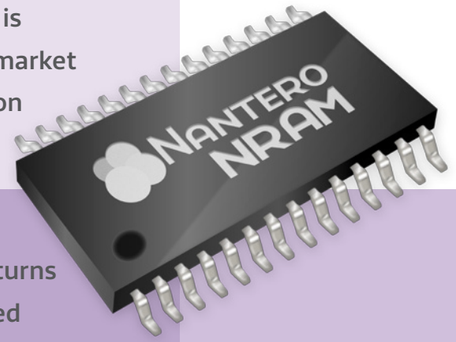
for Unparalleled High-density Memory



Carbon Nanotube used to create Nantero's NRAM®

50 times stronger than steel — 1/50,000th the diameter of a human hair

In the fascinating microcosmic world of modern semiconductor technology, it's sometimes amazing to realize that there are still huge leaps and bounds ahead in both form and function. What may be even more incredible in what is undeniably one of the tech industry's most competitive fields—memory—is that a company like Massachusetts startup Nantero is confidently holding their own on the crest of a market dominated by household name giants like Micron and Samsung.



With a little forethought and considerate collaborative effort—just the sort of stuff that turns your everyday startup into a force to be reckoned with—Nantero's co-founder, president, and CEO Greg Schmergel came face to face with Tom Rueckes, a PhD at Harvard who had an idea to make memory using carbon nanotubes. Of course, as Greg recalls, he knew the basic idea, but the question remained: "OK, but what exactly is a carbon nanotube?" In coming to answer that question, Greg, Tom, and Nantero have found themselves standing deservedly on the leading edge of the development of the memory of the future.

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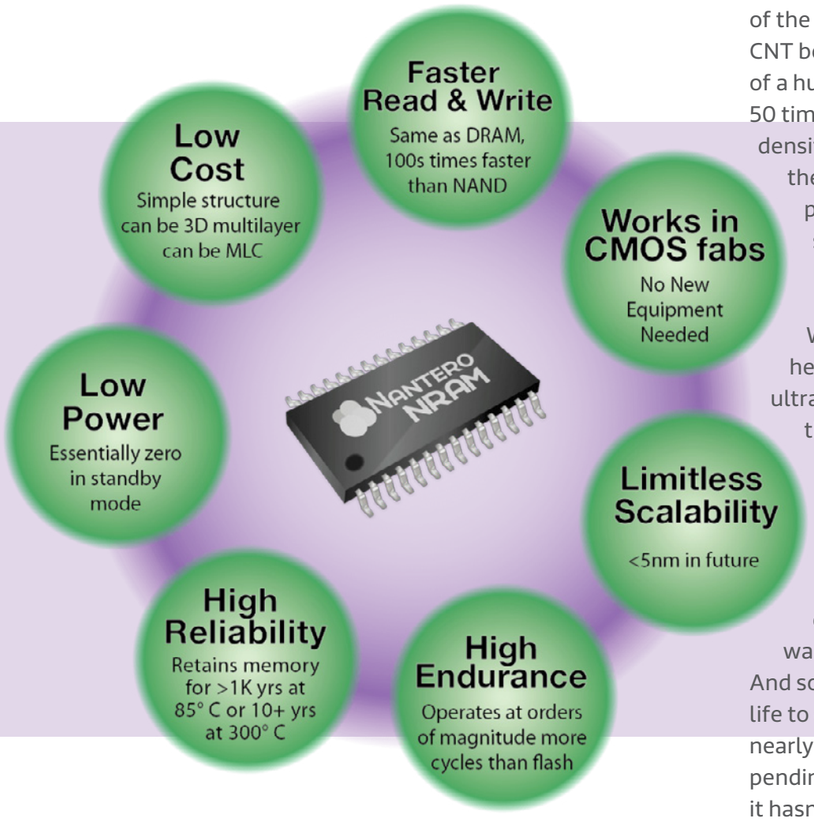

For those unfamiliar with the nature of this game-changing materials breakthrough, the name says it all. Carbon nanotubes are nanoscopic tubes of fullerene carbon in the family of carbon structures named after geodesic dome pioneer Buckminster Fuller, and as such for their general structure of a hollow space surrounded by a thin 'net' of carbon atoms. Some are round, but carbon nanotubes are tunnel-shaped and known for possessing almost preternatural strength and conductivity. Nantero does a good job of concisely summing up the basic idea behind the benefits of using the tiny carbon tubes in semiconductor devices on their website: "Considered one of the strongest materials known, with one CNT being just 1/50,000th the diameter of a human hair, these tiny cylinders are 50 times stronger than steel, half the density of aluminum, and have better thermal and electrical conductivity properties than any other material scientists are aware of today." In all honesty, it's pretty exciting stuff.

What Schmergel did understand, he points out, was "the need for ultra-fast, non-volatile memory" and that carbon nanotubes could be the chance to push the envelope past the capabilities of common DRAM. "Based on that, I spent the next couple of months talking with experts, professors, and so on, and did enough research to know that I wanted to pursue this technology." And so, in 2001, Nantero was brought to life to do just that. Today, the company's nearly 200 granted US patents and pending make it clear that it hasn't been in vain.

Though Schmergel pointed out that it was a bit of a slow road for Nantero at first, he acknowledges wisely that, as things have always gone in the field, truly innovative semiconductor devices "take many years to develop and get into production." He remembered that, "for the first few years, we were really focused on small-scale lab work to demonstrate the performance of the memory and to show that it is low-power enough." In the first stages, carbon nanotubes are grown from iron nanoparticles as a catalyst. To make things work as best as possible in their unique applications, Nantero also had to figure out how to actually make the carbon nanotube material compatible with existing technology. "That led to some intensive work and we hired some of the world's top carbon nanotube experts," Schmergel explained, "and now, we are the only company that has managed to figure out how to purify carbon nanotubes to less than one part per billion of any contaminants."

In a closer examination of what goes into creating these futuristic building blocks, Schmergel points out that "there are two definitions of 'purity': the one we use is what percent of carbon nanotubes is actually carbon, versus iron, nickel, cobalt, etc." Nantero has come a long way in its relatively short lifespan to be able to create the purest form of nanotubes available in the industry. "A few years ago, our standard was less than ten parts-per-billion, but those requirements have gotten more stringent as we've scaled down to smaller nodes. Now it's generally less than one part-per-billion. We can achieve that." The other definition of purity is what percentage of the nanotubes are semiconducting versus how many are metallic. This is something that Nantero's designs don't need to take into account, and it adds to the efficiency of their designs. "We actually don't separate the semiconducting tubes from the metallic tubes. This is because we're using them as nano-electromechanical memory. It actually doesn't matter."

The effectiveness of nanotube-based memory is also strongly rooted in the material's downright Herculean strength. "In terms of endurance, nanotubes are 50 times stronger than steel, so moving them a nanometer back and forth will never wear them out," Schmergel explained. Unlike other materials that wear out by changing their state a certain number of times, nanotubes don't seem to suffer from the same degradation. "We have tested the nanotube switching cycles and have not witnessed any signs of them wearing out at all."

Nantero's NRAM designs have definite proven advantages, with their nanotube structures allowing them to be both as fast as and denser than standard DRAM. NRAM, which is short for Nano-RAM, is non-volatile, too, and has very low energy needs. Outlining some of the design's other unique strengths, Schmergel related that "in terms of other memory, we feel we have a unique combination with very fast speeds and the ability to operate with a DDR4 interface, which a lot of other competitors cannot. We can scale

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down to below 5nm, too, which is another unique characteristic of our memory. Our memory was originally conceived by Dr. Tom Rueckes as a 2-nanometer memory with just two nanotubes moving in and out of contact with each other. If anything, our big challenge was scaling up as opposed to scaling down!"

Another obvious advantage of nanotube-based memory is the ease of manufacture. Because it is a very simple structure and straightforward manufacturing process—"no steps that anyone is unfamiliar with"—manufacturers can expect to find higher yields at lower costs. With just a little deserved pride leaking out from an altogether humble and dedicated demeanor, Schmergel beamed that "the carbon nanotube material is also far stronger than any of the materials used in designs by our closest competitors, so that leads to much more robustness, higher endurance, and faster speed overall."

For those interested more in the specific architecture at work with Nantero's designs, we asked Schmergel what to expect. "We are working on single-layer as well as 3D multi-layer implementations, for even higher densities and lower costs. where we get to multiple layers which are less than 6FSquared. We have shown MLC in silicon as well, can have both multi-layer and MLC as well, since we have many nanotubes-per-bit and can create intermediate resistance states."

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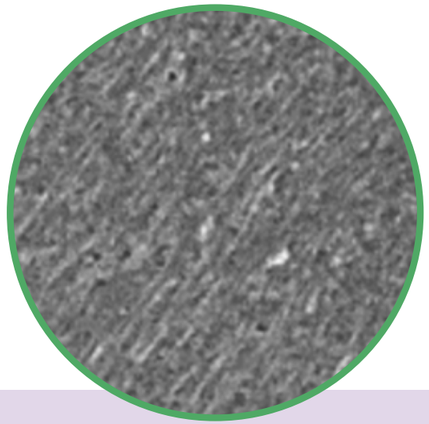

SEM image of the deposited film (or fabric) of crossed nanotubes that can be either touching or slightly separated depending on their position.

It would certainly seem, to this amateur observer at least, that the discoveries of the advantages of carbon nanotube technology are blissfully far from being exhausted any time soon. It can only be fairly assumed that, through the demonstrative innovation of companies like Nantero, much has yet to be learned and gained from the awesome carbon nanotube. EE