

# CARBON NANOTUBE FORESTS: THE NEXT STEP IN ENERGY STORAGE?

## INTERVIEW WITH DR. WAQAS KHALID

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*Dr. Waqas Khalid*

*Dr. Waqas Khalid is a research scholar at the Lawrence Berkeley National Laboratory (LBNL), a project manager at the UC Berkeley College of Engineering, the founder and CEO of the nanotechnology startup company Jadoo Technologies, and a lecturer in the UC Berkeley Department of Physics. In this interview, we discuss Dr. Khalid's work on optimizing and employing carbon nanotube forests for energy storage, biosensing, and beyond.*

**BSJ:** How did your early experiences growing up in Pakistan shape your scientific career, and what led you to continue those studies in the U.S.?

**WK:** I was a very smart kid and a big time mama's boy. The goal was to be the best in school, athletics, and extra-curricular activities. I did the British education system, the A levels, when I was in Pakistan. After that, I got into a very elite high school. There, the goal was to go to the U.S. for higher education. I was actually asked to apply, but my mom flipped out. She said, "Oh, no, you're not gonna go there. You're never going to come back." My dad was okay with it. It took a whole weekend to convince my mom to allow me to go to the U.S. Eventually she agreed, and I flew here. So my drive for excellence and scientific and academic innovation was always part of my being, so to speak.

**BSJ:** Why did you go into nanotechnology?

**WK:** I always wanted to do something really cool and fantastic. I got into a school called Wayne State University in Detroit, Michigan. After the first semester, I got a Global Spartan Scholarship and ended up at Michigan State University. My commute was 200 miles a day, every day, for two semesters. I bought a \$1,000 car and I used it to commute, but after two semesters, the car broke down and I ended up having to move back to Wayne State.

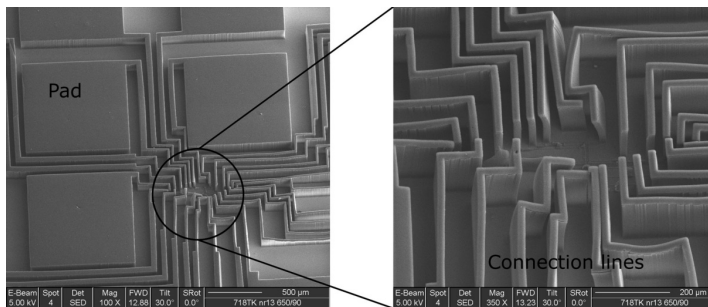
While I was at Wayne State, a lot of things happened. Serendipity, I guess. A company called Delphi, which had been a part of General Motors (GM), got kicked out of GM. They spun out as a company of their own, and they built a state-of-the-art cleanroom for micro-fabrication at Wayne State. Then, a new professor from Caltech joined the faculty at Wayne State. He brought his projects from Caltech on making smart skins and biosensors using nanotechnology. I took a MEMS [micro-electromechanical systems] class with him. I ended up working with him for my PhD. I did my undergraduate, master's, and PhD degrees in five and a half years, all three degrees.



Once we have an image, the question becomes, “How do we know what materials are on that surface?” To answer this question we can use spectroscopic techniques. We can detect chemicals by the interaction of different waveforms on the surface. Then, different analyzers take the data, and a powerful software can then produce an image or a spectrum to let you know what is going on. EDS does all of that. X-rays fall on the surface, and that interaction with the surface gives you the material properties. If you have a compound with carbon, nitrogen, oxygen, iron, or any other kinds of elements, you will get a spectrum with a peak for each of those particular elements, signifying their presence. This was the technique that we used to confirm that we were actually able to functionalize the nanotubes specifically on a surface.

**BSJ:** You noted from your SEM data that the technique you employed to functionalize CNT forest on chip preserves the morphology of the CNT forests. What implications does this hold for potential technological applications of your method?

**WK:** I’ll give you an example. You have a lawn outside. You mow the lawn, take the grass out, and put it on your living room floor. Does that grass have the same morphology and alignment as it did when it was outside in the lawn? Probably not, because grass grows very directionally. It grows vertically, perpendicular to the ground, and it’s nicely organized in a range. But when you chop it off and put it on a surface, the leaves fall flat, and they’re parallel to the surface. That’s what we mean when we say “morphology.” So when you grow nanotubes on a surface, mix them in a solution, and re-deposit them, it’s like the grass from your lawn on your living room floor. In our fabrication process, we can define where to grow these nanostructures—where to grow these grass patches. We provide essential electrical contact with these small patches; it’s like having specific plumbing to water each of these patches individually, wherever they’re grown. Now, this allows you great morphology because you have structures which do not get destroyed and are exactly where you want them to be, since you can define where they are. This fabrication process gives you a platform where you have individually-addressable structures that are very well-defined. Then, you can tap them electrically and chemically to use them in various applications.



**Figure 2a:** SEM micrograph of CNT forest on chip prior to functionalization. The CNTs have been grown in a pattern containing pads and connection lines.<sup>2</sup>

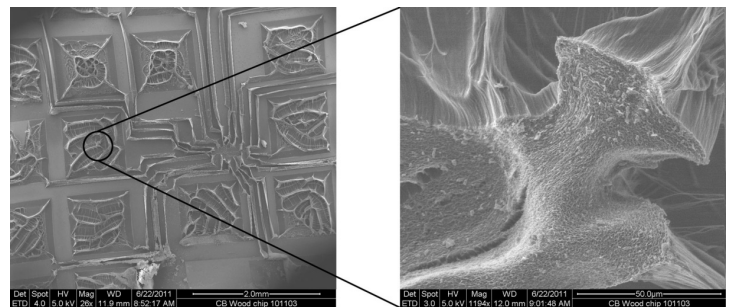
**BSJ:** Continuing our discussion on applications of CNT forest on chip, we wanted to talk to you about your work on energy storage using nanotechnology with Jadoo Technologies. To start, what is the mission of your startup company, Jadoo Technologies?

**WK:** I started this company a while ago. How do you take a cool concept and build an actual product out of it? Given that I finished school so quickly and developed this technology while I was really young, I was ambitious and enthusiastic. I thought that we could change the world by doing things in a new way. While I was in Sweden, I was offered 15 million Swedish crowns, which is around \$3 million, to build this idea and show a working prototype of the technology. But I was of the idea that we could do this in collaboration with academia. Why did we need to burn all this investment capital to get data and lose so much equity early on? We could get the scientific feasibility testing done in a more efficient and effective fashion by grants and collaboration with academia. We could publish papers, distribute the science, and share it with students, rather than having a venture capitalist hold a gun to our head and tell us, “You can only do this, you should not look at any other applications.”

I did a lot of this work while I was in Sweden. I ended up coming to Lawrence Berkeley National Labs to work with Paul Alivisatos, who was the Director of LBNL and is now the Executive Vice Chancellor and Provost at Berkeley. I raised a little grant money here and there and worked with NASA, because NASA wanted to use this technology for monitoring human health in space applications and the human mission to Mars.

While at Berkeley, I started a URAP [Undergraduate Research Apprenticeship Program] project. Since everything was patented, we could use the learning process of rapid prototyping to teach students while getting things done. I became a part of a center called COINS [Center of Integrated Nanomechanical Systems], where a part of my duties was to develop an ecosystem to take technologies developed in an academic environment to an entrepreneurship and industry level.

So, I built the interface for my technology. But to test these things, we had to use these huge commercially available instruments, about the size of a microwave. Okay, you have this very



**Figure 2b:** SEM micrograph of CNT forest on chip after functionalization with an amine group (f-CNT 1 from Fig. 1). Note the preservation of overall morphology: the connection lines to the pads remain well-defined.<sup>2</sup>

small sensing array which can fit on the tip of a hair and has hundreds of sensors. But to use it you need to have something the size of a microwave attached to it, which does not make sense. So, we embarked on the journey of building our own electronics. We also built our own analytical software, using artificial intelligence and machine learning. So now, we have a complete system: the nanotechnology, the interfaces, the electronics, and the software.

This was all done in collaboration with the university, and it's all open source—all this work is shared with researchers at NASA and Berkeley. We are trying to promote the idea that you should share the knowledge, so that rather than everybody doing the same thing over and over again, we can be more efficient. This is one of the many aspects I included when building this new ecosystem, where you could actually mitigate technological and financial risks and create pathways on how to take your product to market. That's the crux of Jadoo Technologies.

**BSJ:** What are the advantages of using nanocapacitors to store energy as opposed to more conventional modes of energy storage such as lithium ion batteries or supercapacitors?

**WK:** The idea is the following: energy storage is a huge problem that humans are facing in the modern world. The evolution of clean energy, like solar panels and wind power, are transforming the energy generation landscape. But to store energy, we all use the recently Nobel Prize-awarded technology of lithium-ion batteries. The problems with this technology are that it's slow to charge, it has a limited number of cycles of charging and discharging, and lithium is a limited resource. So, the question becomes: how do you create a new technology platform where you can store charge in a much safer, faster, and cleaner fashion? Once these batteries die out, we'll be left with a huge amount of e-waste that we'll have to clean up again.

I taught a class at Berkeley where students reviewed the different potential applications of our technology. Energy storage was a winner. Our technology can provide a very unique storage solution. You can create these capacitors, called nanocapacitors, and you can put a lot of them together on a smaller chip. That will give you a capacitance unlike anything else previously built. We were very enthusiastic, performing a lot of calculations and simulations to show that our technology could actually work. Then, I gained access to Lawrence Berkeley National Labs through a proposal process, where I built a few prototypes and showed that the technology really works. We also got some preliminary data, which looks extremely promising. On the size of a postage stamp, we can store enough charge to power toys and electronics, more than a 9V battery. So, if successful, we could actually create an energy storage solution that could charge instantly. You can create wireless energy charging protocols with this technology. The problem is, many people think our technology is too good to be true. Everybody wants to see a working prototype and more data. Who knows what will happen? The best thing is to show a working prototype.

There are also other interesting electric materials coming out in the market called colossal dielectric materials. These materials

don't really exist in nature. What we do is put atomic layers of these materials on our nanostructures and build different materials on top of each other, creating a new kind of material that has really tremendous energy storage properties. Combinations of these cutting-edge technologies allows us to build an energy storage solution that can revolutionize the future of energy storage if successful.

**BSJ:** Could you tell us about your journey as an entrepreneur? What unique challenges have you faced along the way?

**WK:** Life has been full of interesting twists and turns. Once I finished my PhD, I moved to California and started working at a company called Brocade Communications. I went to Mexico to get my H-1 visa situation sorted out. Somebody at the U.S. border detained me and put me in detention for 37 days. They deported me to Pakistan and gave me a five-year ban from the U.S. I was lucky enough that I had a visa for Canada. I ended up in Canada. The U.S. government later said somebody made a mistake, and they fixed the situation and removed my ban. I lost my job during this process, but while I was in Canada, I started working with the University of British Columbia and got exposed to carbon nanotubes. Bringing in my knowledge of MEMS, we developed some biosensors and got some really cool data. This led to me moving to KAUST [King Abdullah University of Science and Technology] in Saudi Arabia and continuing my entrepreneurial endeavors, trying to see how we could build this new idea that I had. These events led to me interacting with Bengt Nordén, to my work in Sweden building up my IP portfolio, coming here to Berkeley and LBNL, meeting NASA folks; life just took its own turns.

## REFERENCES

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2. Johansson, et al. (2012). Covalent functionalization of carbon nanotube forests grown in situ on a metal-silicon chip. *Proc. of SPIE*, 8344. doi: 10.1117/12.915397