

# A Conversation with Dr. Phaedon Avouris: Nanoscience Leader

I met with Dr. Avouris in his office at the IBM T. J. Watson Research Center in Yorktown Heights, New York.

## PSW: Where did you get advice and inspiration throughout your career?

**Phaedon Avouris:** I think the person that had [the most] influence over me was a young assistant professor, Nicholas Alexandrou, who had just come back from the University of Illinois. He was an organic chemist and he brought new ideas about chemistry, mechanistic ideas of electrons flowing to certain sites to react, Woodward–Hoffman rules, and so on. He taught me how to think about chemistry in terms of anthropic principle concepts, maximum entropy, and so on. That helped me [understand] materials—chemical and physical properties. I only interacted with him for a very short time, but he had an influence on the way I think about materials. That's why I think my chemical training was very helpful to me despite the fact that people think I'm doing physics or electrical engineering. I still think like a chemist. It gives you predictive abilities that people trained as straight physicists or electrical engineers don't have. They have to do a simulation or a calculation to predict something when it is obvious to us what is going to happen.

In the States of course it was different. I've worked in so many areas—spectroscopy with Mostafa El-Sayed,<sup>1–5</sup> and then I came here [to IBM] and worked in surface science, first collaborating with Joe Demuth<sup>6–15</sup> and then on my own—nano and nanotubes, and STM was a big thing; I spent many, many years on that, as you know. Graphene and other carbon [materials]—both experiment and theory. It's been a good life!

## PSW: What made you decide to move toward carbon nanoelectronics?

**Phaedon Avouris:** Well, I was just reading the first papers on nanotubes and I was

thinking about intermolecular forces at the time. I had a discussion with Rick Smalley, who was telling me that nanotubes are beautiful—very strong and rigid, and also defect-free. Somehow that did not go along with my notions of how they should behave. My first studies were actually AFM [atomic force microscope] images of nanotubes and I noticed that they were curving going around steps.<sup>16–18</sup> I had images that actually appeared on the cover of the *Journal of Physical Chemistry* of overlapping tubes.<sup>16</sup> The upper tube would fold around the lower one, and they looked like cooked spaghetti to me, rather than these perfect rigid tubes. So, I started looking at them. (I had just finished my atomic manipulation studies of silicon.<sup>19,20</sup>) I looked at how they respond to forces and again I saw them folding and being dragged (Figure 1). I could position them, again looking very much like cooked spaghetti. That intrigued me.

I realized one thing: physical chemistry has concentrated on molecular systems. It was the structure of the molecules, their spectroscopy of whatever wavelength range, their reactivity, and magnetism (if any). The only thing that was never done was to measure their electrical properties. That was the difference from condensed matter physics. That was primarily because nobody knew how to address an individual molecule. That intrigued me, that we know just about everything about the molecular world but do not know... electrical behavior. I had read as an undergraduate, in a journal or popular science magazine, something about intercalation of iodine in starch and how that makes the materials conductive. I'd say, "you know, there must be something to electricity that chemists need to get involved—molecules and electricity." I got intrigued by electrically addressing molecules and it looked to me that nanotubes are the ideal system. Soon after I got involved, Cees Dekker got tubes from



Dr. Phaedon Avouris.

To hear Dr. Avouris' advice to young scientists, please visit us at the audio page of <http://www.acsnano.org/>.

Published online December 28, 2010.  
10.1021/nn1032032

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Richard Smalley,<sup>21,22</sup> while we were doing the same thing.<sup>23–26</sup>

That year, we both came up with the first nanotube transistors and that got me involved in electrical studies of nanotubes. I was also involved in molecules, but was primarily looking at conceptual aspects and what would be different there. Contacting them by the techniques I had available would not be easy. So, that was the start of the nanotube... first, the mechanical properties, then, the rigidity, then addressing them individually.<sup>27,28</sup> In the environment of IBM, [we asked] what can you do with them? Are they useful? We made the first transistors and then moved to some simple logic circuits.<sup>29,30</sup> At some point, my previous background in spectroscopy kicked in. I was always interested in nonradiative decay, so I started looking at light emission.<sup>31–34</sup> For nanotubes, that started as electroluminescence and what generates the light; more followed.

**PSW: What do you see as the future and potential advantages of carbon nanoelectronics?**

**Phaedon Avouris:** Well, there are two aspects of this. There is never a direct correlation between what you find now and what possible uses emerge in the future. Now, we have a certain view of what electronics technology or optics technology are, but that does not mean

It's what you *learn* that forms the basis for innovation for the future.

that the future will have FETs [field-effect transistors] and LEDs [light-emitting diodes]. It's what you *learn* that forms the basis for innovation for the future. I think nanotubes have provided the basis for understanding a lot of what is possible at the nanoscale and in the molecular world. I'm not sure that the technology will depend on just that. Right now, technology involves factors that are technological but are financial also.

In any case, nanotubes may have superior properties at small scales compared to any other material. Is that enough? No. It depends on how manufacturable they are, how cheap they can be; if what you gain can justify the expenditures for new facilities, how competitive they would be in the market. These are beyond the scientists' concern. I think that the main contributions of our studies are not toward technology, but rather toward understanding nature and as a basis for future technologies. This could be what we're working on now or could be completely

different, but utilize the knowledge we gain.

Making more specific nanotubes, well-defined structures—there are ways to bypass that at least temporarily. If you look to replace silicon, then you need all these well-defined tubes with the same band gap, so they can switch simultaneously. But, if you are looking for other properties, for example you want to have light, flexible devices—there are great needs developing for that—then you can bypass the issue of synthesis by having arrays that effectively average the behavior of nanotubes. If you manage to have a homogeneous mixture, then you can get good performance. Not competitive with silicon—that is not the goal, to replace silicon, but for other applications. For example, the military wants electronics that soldiers can wear that are light and flexible. There is a big market that will proliferate and require electronics that are molecular, nanotubes, whatever.

Carbon electronics, carbon in general, is spreading everywhere. Again, not necessarily as a replacement for silicon and not because of "Moore's law." There are many [possible applications], and I think many experts would agree with me. I just came from the DRC [Device Research Conference] and there was a plenary talk there about the future of electronics and the speaker [Dr. Kensall D. Wise, Center for Wireless Integrated MicroSystems, University of Michigan] insisted that it is not computers, it is bioapplications.<sup>35</sup> In particular, all kinds of devices for hearing, for vision, for Parkinson's disease, which he demonstrated in videos, that *enable*. The way he put it was really good: it is quality-of-life applications. Not the fastest computer in the world, but something that individuals can use and benefit from.

I think in order to go beyond what we have today, you have to do basic science. You have to *understand*. I think what research in an environment like IBM does, because we constantly compare with ultradeveloped, ultrafine technology, we go to the details and try to reach control conditions and well-defined properties. The rules may be re-

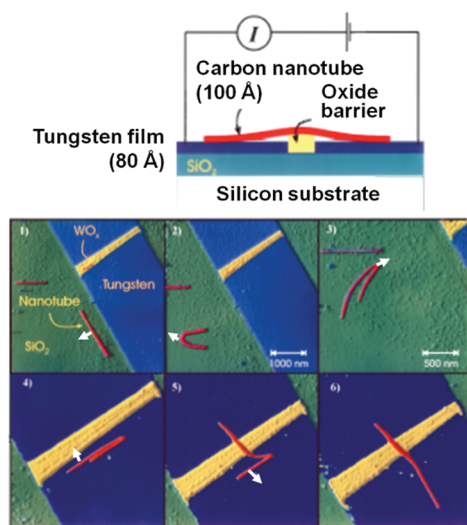


Figure 1. (Top) Schematic of target structure for measuring current through a carbon nanotube. (Bottom) AFM tip manipulation of a single nanotube on a SiO<sub>2</sub> film and placement of it across an oxide barrier previously fabricated by AFM-oxidation of tungsten. Figure courtesy Phaedon Avouris.

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laxed if the technology does not need it, but it is good to know exactly what does what. Then, you decide if you need that [level of] control or not.

**PSW: Can you tell us about high-speed graphene transistors?**

**Phaedon Avouris:** Graphene is one of the most intriguing materials; we knew that for a very long time. We always used it as a prototype structure to discuss a number of properties.<sup>36</sup> You'll find it in all organic chemistry books—it was not called graphene then. I think graphene was accepted as a name by IUPAC in 1995, but we did not *have* it. It was used for discussing nanotubes and so on. Surface scientists knew it, but it was a nuisance. You would heat your nickel or platinum crystal and it would segregate on the top, so you had to etch it away. Now people are trying to generate it using the same materials!<sup>37,38</sup>

Once we started studying it, [we found that] it is unique. Physicists stress the fact that it behaves like a relativistic electron system. I'm trying to make the connection. It is very simple, but it is usually complicated by arguments that it is due to pseudospin conservation, that electrons do not get backscattered. Chemists can easily understand it because there are  $\pi$  and  $\pi^*$  states—they're orthogonal and therefore do not interact. Dispersion is linear again exactly because if you have two orthogonal states, so there is no avoided crossing. I wrote a perspective for *Nano Letters* on demystifying this part.<sup>39</sup>

The result is that you have special properties that come from the structure and you have special properties that come from the very strong covalent

bonds. The net result of these two is you have very high stiffness; the frequency of the optical phonon is  $1600\text{ cm}^{-1}$ . For silicon or GaAs you have  $500$  and  $300\text{ cm}^{-1}$ . So, electrons do not get scattered by optical phonons. Second, they have zero rest mass and the Fermi velocity is very high. With the symmetric band structure, you have outstanding transport properties.

If you expect to get ultrafast electrical transport, this is the material.<sup>39–41</sup> Mean free paths are typically a few hundreds of nanometers. All these years, people tried to get in the ballistic regime in silicon and it never happened. With graphene, you *could* get there.

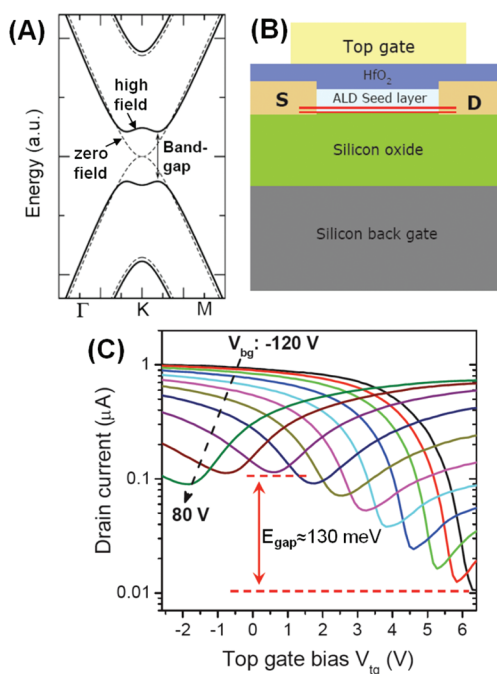
Even with relatively modest mobilities, we get  $100\text{ GHz}$  at  $250\text{ nm}$  [feature size].<sup>40</sup> Now silicon is down to  $22\text{ nm}$  [feature size]. But, at  $250\text{ nm}$ , silicon can only get up to  $40\text{ GHz}$ . If you start scaling, hopefully graphene will go higher. That does not mean that it is simple. There are all kinds of issues that develop. One is the issue of contacts. We have to discover why we now have contacts that can be as low as  $200\text{ }\Omega\text{-micrometer}$ . People that have pub-

lished in the literature have  $k\Omega$ . We're trying to understand and reduce it and we think we know how. There are other issues, stress and so on. In principle, in the end you'll be RC limited, but I think it could approach terahertz.

The other advantage is that we do not need MBE [molecular beam epitaxy] systems and expensive chemicals—it is carbon! We may now use rather expensive substrates to grow it, like silicon carbide,<sup>42</sup> but it does not have to be that way in the future. There are many ways to form graphene. Graphene is a stable form of carbon and eventually almost everything converts to graphene. It is a matter of finding the best conditions to eliminate defects, to control growth, and so on.

Graphene does not have to be monolayer. That is another thing, the physics changes as you go from monolayer to bilayer and trilayer.<sup>43</sup> But from the device point of view, even the bi- and trilayer properties are good enough for certain things.

What you do not have is the band gap. But again, we have opened band gaps. We have reached up to  $150\text{ meV}$ . It is not enough for digital devices, but



**Figure 2.** (A) Band structure of bilayer graphene at zero applied electric field and at a high perpendicular field. (B) Schematic of the double gate (top and bottom gates) transistor configuration used to apply the field. (C) Drain current versus top gate voltage for different bottom gate biases varying from  $-120$  to  $+80\text{ V}$ . Gate oxide:  $300\text{ nm}$  of  $\text{SiO}_2$ . A current on/off ratio of 100 was achieved at  $300\text{ K}$  and a band gap of  $\sim 130\text{ meV}$  was generated. Adapted from refs 44 and 45. Copyright 2010 American Chemical Society.

you can do a lot of things, for example, in photonics. We know how to do that because the reason graphene does not have a band gap is that you have two atoms in the unit cell and they are acting identically and are in the same potential. In a bilayer, you have four atoms in the unit cell, and they involve different layers. If you polarize them, if you induce charge transfer between the two layers, then you open it [the band gap] up (Figure 2), and that is what we've done.<sup>44</sup>

It is also a matter of getting the right insulator. The insulator is the most difficult technological problem in these devices. In both graphene and carbon nanotubes, you have a  $\pi$  system, which is totally exposed. If you enclose it in an insulator, it is going to interact. First, it is not easy to deposit it, because it does not stick, so you do not form uniform layers. If it does stick, it binds the  $\pi$  system and does not work. So you require a very subtle situation—sticking enough but not too much. That is a very delicate technology. We use atomic-layer deposition and pretreatments to introduce layers that will prime the surface but not interfere. All these things have to be worked out.<sup>46</sup>

At IBM, with the support of DARPA, we're working for high-frequency electronics, but it could also be used

for many other things. There are already markets for transparent windows, conductive windows, replacements for touch screens—that is also not very restrictive. It does not require all the precision that we're working on. I think you are going to see applications and markets developing, already some companies seem to be very serious about coming up with products in the near future.

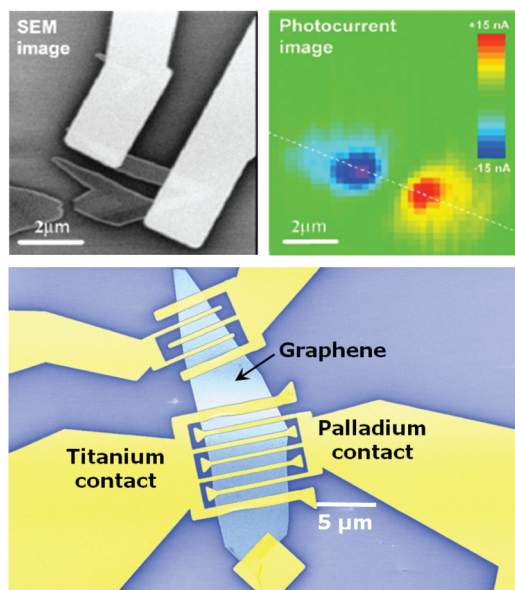
**PSW: You have discussed the difficulty in creating passive elements.**

**Phaedon Avouris:** Yes, at this point, if you use graphene as a substrate for depositing passive elements on top of it, you have to work out the deposition procedures. It is not the same as silicon and you cannot anchor things to graphene, because you would tie down the  $\pi$  bonds.

Another thing that we're exploring is thermal management; it is a serious issue. In commercial devices, heat that is generated by passing a current is dissipated through phonons that couple the heat out. Silicon is coupled to  $\text{SiO}_2$ ; heat can flow from one type of bond to another. But for graphene, nanotubes, and molecules, you do not have covalent bonds, you have van der Waals

I think nanoscience is a mixture of everything. You need to know chemistry, you need to know physics, and depending on what part of nanoscience you are in, you have to know electronics, electrical engineering, or biology.

bonds, and big separations. The van der Waals phonons are at very low frequencies, so you cannot convert a "big" phonon to many little phonons with high efficiency. So, devices—molecular devices, graphene, nanotubes—heat up, and that is a limiting factor in performance. You have to figure out ways for the energy to flow across, and that is what we're exploring. Experimentally, what we find is that it is actually a lot better than you expect. We are exploring other mechanisms for transport that are not traditional—coupling to surface phonon-polaritons.<sup>47</sup> It is not new; it has been discussed in the past in a different context. For example, when a fast electron approaches a polar surface, how it loses energy. Jerry Mahan has discussed that.<sup>48</sup> It has not penetrated the device field, because devices are thick. The fields produced polar surfaces decay exponentially away from the surface, but graphene, nanotubes, and molecules are right at the surface. They can couple to these fields and dissipate energy. How important that is, is what we are working on. It may be one way we can enhance dissipation. Thermal engineering at the nanoscale is another area where we could learn a lot. It will have very broad applications in sensors, biomolecular devices, and certainly in electronics.



**Figure 3.** Photoexciting at different positions on graphene contacted with Pd gives currents of opposite sign (right).<sup>49</sup> Scanning electron microscope image of interdigitated electrodes on graphene in which different contact metals induce a lateral electric field (left).<sup>39,49</sup> Figure adapted from refs 39, 49, and 50. Copyright 2010 American Chemical Society.

**PSW: You also have made recent advances in fast broadband photodetectors based on graphene. Can you tell us about those?**

**Phaedon Avouris:** The reasons that make graphene ideal for fast devices also make it ideal for fast photonics. Graphene has very high absorption. We say it is a transparent material, but in reality, if you think about the fact that it is a single atomic layer thin yet absorbs 2.3% of all incident radiation of *any* wavelength with almost constant efficiency, it is unique. With the kinds of materials that are used in photonics like InGaAs, if I remember correctly, to get the 2% absorption you require something like 200-Å-thick material.

This is a strongly interacting system for light, and the carriers move fast. In principle, both electrons and holes move very fast, unlike in the III–Vs. The key problem has been that being a semimetal, graphene has very fast recombination. Indeed, you do not see luminescence from graphene. If you were to excite bulk graphene, nothing would happen. If you were to apply a bias across graphene, you could see a photocurrent, but it would be on top of a huge dark current. That discouraged people from looking for photonic applications. In our studies of what happens in graphene contacts, we noticed that we can generate net photocurrents using SNOM [scanning near-field optical microscopy], if we excite near the contacts.<sup>39</sup> That is because the electron–hole pairs are separated by the electric fields that are produced by band bending. So, we use that for photocurrent generation and photodetection. We found that we get extremely fast photoresponse, as fast as any measurement systems that we have here at IBM.

**PSW: What are the limits?**

**Phaedon Avouris:** The limits are that you [have to] excite only one contact, say close to the source contact.<sup>49</sup> If you excite close to the drain contact, the electric field will be opposite. If you illuminate the entire device, you get no net photocurrent. So, that is a limitation. Of course, you could just mask one

of the contacts, but that is not the solution for us. We also wanted to increase the yield, so we wanted to increase the area. Recently, we tested another approach where we used interdigitated electrodes made of two different metals (Figure 3), to make the band bending asymmetric, one with a high and one with a low work function, titanium and palladium, for example. We make the potential profile between the contacts sloping all the way. That worked very well. We increased the output 1300%, and we could use it to detect optical data streams; the maximum we could generate and detect was 10 Giga-bits per second.<sup>50</sup>

**PSW: What about carbon nanotube separations?**

**Phaedon Avouris:** We have seen a lot of advances in separations. I have been working with Mark Hersam and we're using his nanotubes<sup>51</sup>—not separation by chirality but separation by type.<sup>52–54</sup>

Some are for high-frequency measurements. We're making arrays of nanotubes for flexible high-frequency electronics. I'm very happy with the 99+% control that he gets. Still, this is not the solution. For high-end devices, the nanotubes have to be identical, but it is a vast improvement. I heard that there are some other column-based techniques that yield very good results, too. They provide some stimulus, but I don't think they're so easy to base technology on. First, the yield is low. Second is a problem with nanotubes and graphene—they are insoluble. You need to solubilize them, and in order to do that you have to add things, and then it is very difficult to remove those added things; you are stuck with them.

I cannot predict what the future will bring, but the solution has not been found yet. I think people realize that. For now, experiments can get more and more sophisticated and we're getting closer and closer to well-defined systems, but we're still far from a technology.

**PSW: How do we look forward to where conventional technology is going to be in order to make a fair comparison and to see if it will even be possible to "cut it off at the pass"?**

**Phaedon Avouris:** Looking at where technology will be? We do not know! We develop a knowledge basis for people to borrow from and to develop their ideas about what will be needed in the future. It is not that we can predict what is needed. A few years back, we did not even have this idea that we needed photovoltaic energy or green chemistry.

Needs, or perceived needs, develop as a function of time. [Who knew] the transistor, which was intended for hearing aids and telephony, would find all these applications? You do not develop something for a specific use; you develop something to understand its potential. You have certain ideas and if you work for IBM, you want it to be used in electronics, but it could be used in other areas; you never know.

**PSW: Is there a strategy for assessing applications outside of electronics at IBM?**

**Phaedon Avouris:** I do not know if IBM would be interested in manufacturing a particular product. They may also sell intellectual property to another company that may want it.

**PSW: How have you seen your scientific efforts evolve?**

**Phaedon Avouris:** Work has changed dramatically since the early days where you had a little lab and you went in and used one instrument like an STM [scanning tunneling microscope] in a vacuum chamber and put a sample in and measured as a function of this and that, the temperature and the field. Now, at least in my area, it has become a much more complex affair. Equipment is dispersed all over the place, and making a sample is 99% of the work. You use all kinds of patterning and positioning techniques and analysis techniques and wiring and high-frequency measurements, all distributed in different laboratories, officially owned by differ-

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ent people. When you present it, it takes just a few lines in your paper to describe 99% of the effort.

Then, you go and measure and make a few graphs and again spend a long time trying to figure out what it all means. The distribution of effort is very different from the old-style work that was just one person, one room, and typically one piece of equipment. It has become a real effort to get things done, with long delays; it requires a lot more effort. I think it is very difficult now for small groups in small places to make substantive contributions that have implications. That is why I think you see interdisciplinary centers and big collaborating groups at universities getting together. Small-scale science has become more difficult. It is not absent, and it can be very good if people are innovative, but it is more difficult and more difficult to support.

**PSW: How have you seen corporate and industrial research change over time?**

**Phaedon Avouris:** It has changed, as everything else in our society has changed.

I think from the point of view of industrial research, it is understood that right now it is impossible to cover everything, so we depend more on input from universities. One thing that I am concerned about is that [people at] universities do not know all that much about technology. In the past, Bell laboratories, IBM, and certain other companies have provided, have seeded, new academic people who knew the require-

ments and the limits of technology. These people are getting older and retiring. If industrial research ceases, I am afraid that we will miss something very important.

**PSW: Why do you like nanoscience?**

**Phaedon Avouris:** I think nanoscience is a mixture of everything. You need to know chemistry, you need to know physics, and depending on what part of nanoscience you are in, you have to know electronics, electrical engineering, or biology.

I'm motivated primarily by learning new things. It *requires* me to be involved in many scientific areas, and I think that is exciting! I think it is good for disciplines in that it provides a unifier of physics, chemistry, engineering, medicine, biology, whatever you have, by bringing common techniques like imaging techniques, lithography techniques, deposition techniques, all that, that are common to everybody and sharing what has been found in the different fields.<sup>55</sup>

Physics provides new principles, materials science and chemistry provide new materials and configurations, and the architecture [comes] from other fields. It is enriching. Nanoscience builds a new vision of science as something united, not compartmentalized, without strict disciplines and barriers. I hope these unification projects continue. I think it is the prototype *and* like the old days when we had scientists who knew everything. People ask me where do I go—what do I study to become a nanoscientist? It is just read your physics, your chemistry, everything, and be sure that you focus on the basics. Try to understand things.

That is what I like about nanoscience besides all the promise of new products. That will happen, too. I think we are likely behind on that, because we have made so many promises. That is a danger; we have to watch out for hyping. Maybe some of that is not from the scientists, but from journalists and so on, but it hurts. Eventually people expect miracles and miracles don't happen. Technologies take a very long time to develop; it's not around the corner.

[Literature citations and figures were added after our conversation to assist and to direct the reader to relevant publications.]

— Paul S. Weiss

*Acknowledgment.* We thank Holly Bunje and Heather Tierney for help in preparing this Conversation, and IBM for supporting my visit to their T. J. Watson Research Center.

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