A Conversation with Dr. Masakazu Aono: Leader in Atomic-Scale Control and Nanomanipulation

I met with Dr. Masakazu Aono for an afternoon and evening in Tokyo in mid-November. Dr. Aono led the first center in the world devoted to nanoscience and nanomanipulation, called the Aono Atomcraft Project. More recently, he and the team that he leads were awarded one of five World Premier International (WPI) Research Centers by the Japanese government.[1] While open to all fields of science, two of the awarded centers focus on nanoscience and nanomaterials.[2,3]

PSW: Let's start with a discussion of the Aono Atomcraft Project and then talk about your new WPI Center. What were your goals when the Atomcraft Project started?

Masakazu Aono: In 1982, I read the paper by Gerd Binnig, Heine Rohrer, and Christoph Gerber on the [Si(111)] (7×7) surface.[4] My colleague gave me that paper and just after reading it, I really *jumped* from my chair. I thought, "We can use this technique to manipulate atoms! Manipulating atoms is much more interesting than observing atoms!"

I wanted to start that kind of research, but the year before, I invented a powerful new method to analyze surface and subsurface structures—a new type of ion scattering spectroscopy, impact collision ion scattering spectroscopy.[5] I published that in 1981, and after that, suddenly I was invited to five or six international conferences, including the APS [American Physical Society] March meeting. I was very busy doing ion scattering experiments.

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So, I started STM [scanning tunneling microscope] studies in 1986, after moving to RIKEN (before that, I was in Tsukuba, at the National Institute for Research in Inorganic Materials). First, I prepared a very sharp tungsten carbide single-crystal tip; by cleavage a very sharp tip apex is formed. By using it, I did nanoindentation experiments, not atom manipulation. The next year, I received a phone call from JRDC, the Research Development Corporation of Japan [now the Japan Science and Technology Agency, JST]. They asked me, "Are you interested in organizing an ERATO [Exploratory Research for Advanced Technology] project?" Of course, I was very much interested in that. They asked, "What is your research subject?" I wanted to study manipulating single atoms, and I said so. They said, "Oh, that seems to be very interesting; why don't you start the project?" I didn't write any proposal! Those were good days, almost 20 years ago.

PSW: And what happened at the beginning of the Atomcraft Project?

Masakazu Aono: That was a very challenging day for me. I was 42 years old. In Western countries, 40 is old enough, but in Japan, it is still young. It was not so easy to get good scientists, so I started with my colleagues. This project was not so large, only about 10 scientists.

Of course, there were also good advisors—Heine [Rohrer], Young Kuk (Young Kuk was young), Maki Kawai, Masaru Tsukada (a theoretician), Toshi [Sakurai], Tien Tsong, and Stan Williams.

Dr. Masakazu Aono at Ginza Ippodo Salon, his wife Keiko Aono's beautiful art galley in Tokyo, Japan.

To hear Dr. Aono's advice to nanoscientists in English and Japanese, please visit the *ACS Nano* podcast page at http://www.acsnano.org/.

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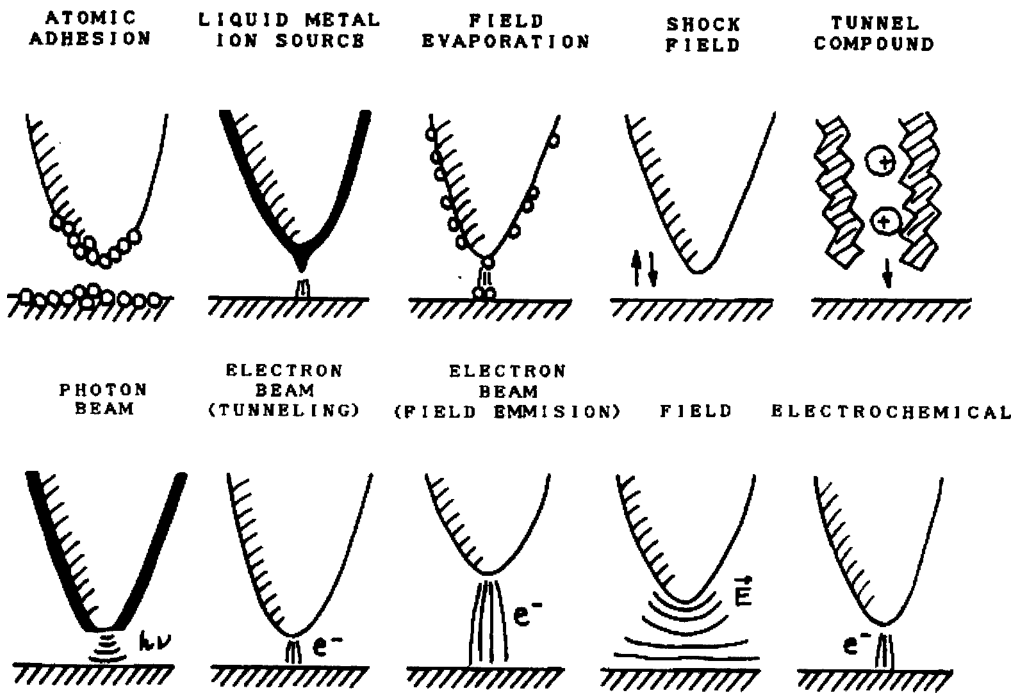

Figure 1. Sketch from the early days of the Aono Atomcraft Project, courtesy of M. Aono.

PSW: What were the leading accomplishments of the Atomcraft Project?

Masakazu Aono: We started this project in 1989, and in 1990 or '91, after just one year, Don Eigler did that famous work of arranging xenon atoms into "IBM".[6] At that time, I couldn't sleep for a week.

I decided the reason why he could do that is his STM is *so* stable at 4 K, everything is cooled down to 4 K. My colleagues wanted to imitate his method. But I thought it would take two years at least to follow him, so I decided to do all experiments at room temperature to make nanostructures that are stable at room temperature, because "IBM" letters evaporate at 20 K.

So, I decided to do atom manipulation at room temperature. The most important material is the semiconductor silicon, so we mainly focused on atom manipulation on silicon surfaces. But, as you understand, that is difficult, because the binding energy is large. Anyway, we developed three methods: how to extract atoms, how to displace atoms, and how to pick up atoms on the tip apex and then supply atoms. [See Figure 1, which shows a sketch of a number of atom manipulation methods proposed as part of the Aono Atomcraft Project.] If these three are possible, we could do anything.[7] But, they are very difficult.

PSW: How long did that project last?

Masakazu Aono: All ERATO projects were for five years.

PSW: Japan is quite different from the West in having fixed projects that terminate abruptly. I recall that just after the Atomcraft Project, you had some tremendous successes on your own.

Masakazu Aono: Let me say that we studied not only single-atom manipulation but also how to make chemical reactions and how to deposit materials—atoms from the tip [Figure 1]. I had an idea to make an STM tip with a superionic conductor in which the metal atoms are moving around like a liquid. I thought, "If we apply a voltage between the tip and sample, we will be able to deposit atoms one by one, to draw atomic chains." We did that kind of experiment at the end of the Atomcraft Project, but that was not successful because the selection of ionic conductors was not so good. We started with alumina containing potassium. That was unsuccessful. We switched to a new material—a titanium oxide layered compound, also with potassium. That was unsuccessful.

And after ending the Atomcraft Project, fortunately I could start a CREST project [Core Research for Evolution Science and Technology]. That was the very first year of the CREST program. During the CREST project, I succeeded in drawing. We used silver sulfide, and we succeeded in drawing silver lines on flat silicon surfaces, along the [STM] scanning line.[8]

One day, my postdoc who was doing those experiments came to me and told me that something strange occurs. The silver sulfide STM tip retracted more than 100 nm [from the surface]. And, if we changed the polarity of the voltage, the STM tip came back again to the surface. I thought, "Oh, this is deposition of silver atoms!" I immediately came to the idea of a switch. So, we cut off the feedback circuit and did the same experiment. And, the silver protrusion made a bridge to make a gap turn ON, and we succeeded in turning it ON and OFF at 1 MHz. So, I started to use that phenomenon for a switch, but at that time, I thought, "Oh, this is certainly interesting! But switching speeds will be very slow. Anyway, why don't we make an experiment?" When we repeated the

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experiment, the speed was very high.[9–11]

During that period, Heine Rohrer came to Japan and gave lectures here and there. At that time the title of his talk was "Small is Different". He showed five examples of where, if the space becomes small, new phenomena happen. One of those is if the distance is very short, diffusion is very fast. For example, in the case of the diffusion, in which diffusion occurs in 1 s for 1 mm, the diffusion rate goes as the square root of time, so if dimensions become small-...[diffusion is faster]. And he talked about that. At the time, I did not recognize its importance. After I made that switching experiment, I suddenly understood. In the case of 1 nm, atomic movement is *very* fast. And so, we constructed ON/OFF and NOT gates using only atomic switches. NEC Corporation was interested in that.[12]

Five years of CREST had passed already. I started a SORST [Solution Oriented Research for Science and Technology] project. We made a real collaboration with NEC Corporation, their Tsukuba Research Center, Fundamental Research Laboratories. Last year, that group moved to the Sagamihara site of NEC—production is right there. They are studying how to put our atomic switches on programmable ICs [integrated circuits]. As you know, if we produce a typical IC, it is impossible to change the circuit. NEC sells various ICs for Sony Playstations, Toyota cars, or Honda cars—they are all different. But if they make a so-called ASSP, application-specific standard product, that consists of relatively large logic cells connected by switching circuits, then NEC can produce only one type of IC. If Sony asks them to use it for Playstation, NEC just changes the switching circuit and sells it. And if Toyota asks them, they change it, and sell it. So that is very efficient in terms of design, time of design, and cost of production.

They are interested in atomic switches, because usual transistor switches are volatile. Usually, a single switch consists of SRAM and a pass transistor. We need a RAM and transistor. So, a single switch requires 120*F*—as you know "*F*" is a minimum fabrication scale, but our atomic switch is only $4F^2$, 1/30th the area. If they want to produce a high-performance program on an IC, the switching circuit becomes very large. But, if they use an atomic switch, they can produce a compact IC.

Let me say one more thing about atomic switches. Atomic switches have some kind of learning ability. We have a gap, and if we apply a short pulse, a protrusion grows, but not yet to ON. A second voltage pulse is applied, and this grows more, but nothing happens. After several pulses switching ON occurs. We see the same thing switching OFF. Now, we are going to construct a circuit. Sometimes the silver sulfide islands are random, and we apply the voltage from island to island, and paths are formed.

PSW: It follows a percolation path?

Masakazu Aono: Yes, after many, many pulses. By using that effect, we are going to construct some kind of neural network. We have to place many silver sulfide islands, and the gaps are very poor. So, we will use your technique, the molecular-ruler method,[13] after learning it from [Hirofumi] Tanaka.

PSW: You had another beautiful experiment with polymerized "molecular lines" from that time. Can you tell us about that?

Masakazu Aono: I found an effect, and I thought, "Maybe this is a very general phenomenon. If we prepare a molecular layer, we'll be able to make a chain by polymerization." We tried many, many molecules that were unsuccessful. So far, only four molecules, diacetylene compounds work.[14] The chain size doesn't matter, but diacetylene is required. That is not so interesting.

But that wire—polydiacetylene is a good conductor. We showed that if we induce many electrons or holes, we can make a metallic wire.[15] The orientation is limited; that is determined by the original monolayer. We tried several applications. We are now making a FET [field effect transistor]; that was successful. We studied how to make a front electrode, we have an insulator surface, and we have two fabricated electrodes. After that, we polish it completely flat, so the electrode and insulating parts are flat.[16] So, if we create a molecular wire, the molecule is straight. We place a gate, and we observe an FET effect. But this FET is not so interesting.

We are now going to make a wire and place two electrodes. We apply a positive voltage and a negative voltage. And we can induce electrons and holes to recombine, to emit photons. I'm interested in single-photon emitters for quantum information devices. We found this effect six years ago, but we have not yet succeeded to use it for real devices; we tried many recipes, but that was very difficult.

PSW: You developed multiprobe STMs. What is their current status?

We constructed multiprobe STMs that have two, three, or four probe tips that can be operated independently. Each probe tip can record high-resolution STM images, but our main aim is to use the probes as nanoscale electrodes for electrical conductivity measurements at the nanoscale. By using the multiprobe STMs, we have measured the electrical conductivity of nanostructures such as carbon nanotubes, fullerene films, and metal nanowires.[17,18]

PSW: What are the focuses of the new WPI Center?

Masakazu Aono: At the new center, we have many researchers. Materials science has wide variety, and sometimes serendipity is very important in

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developing new materials. So, I decided not to focus on a small number of subjects.

For at least the first two or three years, I'd like to ask researchers of MANA [International Center for Materials Nanoarchitectonics][2] to do their own research. But, I have three dreams: (1) room-temperature superconductors, (2) new materials for a brain-type computer, and (3) a completely new type of solar battery.

So far, a brain-type computer is made by software, or combinations of existing devices, such as transistors. I'd like to make a new brain-type circuit using novel materials in which the material itself changes with time depending on signals from the outside. And if we learn from our brain, this is not electronics but ionics, or electro-ionics or something like that.

PSW: And chemical transmission.

Masakazu Aono: So, I think the era of electronics has to end. We should move to ionic circuits. We have to produce ionic circuits, maybe at first electro-ionic, or ion-electronic circuits. In the future, we have to combine photonics. So photo-electro-ionics, or something like that. Our eyes are doing that.

Also, we should really consider solar energy. We don't need to transport power in the case of solar energy. But, for the case of a silicon solar cell, silicon needs much electric power and *water*. At present, even if we produce a solar battery, if it does not last 10 years, the energy gain is negative. So, we have to develop a new type of solar battery. Is this a dream?

For these three, we have small seeds already. Room-temperature superconductivity is not a complete dream. At NIMS [National Institute for Materials Science], we have found that if we dope diamond with boron, highly doped diamond changes into a superconductor. Some theory says that is okay; if we dope boron into carbon, the diamond is so disturbed. So, we have some idea of how to induce charge without doping, and we are going to measure the T_c [superconducting transition temperature].

PSW: Are most of the people in the new center at NIMS, or do you have other collaborators elsewhere in Japan and abroad?

Masakazu Aono: At present, we have six satellites. One is at UCLA, the California NanoSystems Institute with Jim Gimzewski. At the Nanoscience Centre at Cambridge, Mark Welland is the PI. And Zhong Lin Wang at Georgia Tech. We are going to construct a theory group; Christian Joachim is one PI. That is four overseas satellites. We have two PIs from Tsukuba University. We have one PI from Tokyo University of Science, who is studying superconductor qubits, and he is doing very nice work. In Japan, we are going to make a collaboration with Hokkaido University, Nagoya, and Kyushu, because the Tokyo, Osaka, Kyoto, and Tohoku groups already have this kind of center. It is a little harder to court some professors from Tohoku University as PIs.

PSW: Because of the other WPI Center there?

Masakazu Aono: Yes, my friend Yoshinori Yamamoto is the Director. But personally, we have been collaborating for a long time with many professors at Tohoku University. I don't know the present status of the Tohoku Center, but we will go slowly, in low gear, and push the accelerator after one or two years.

PSW: You'll see what happens first and follow promising leads as you did in the earlier projects?

Masakazu Aono: Yes, I'm always a slow starter.

PSW: This is a much bigger project than the earlier ones, yes? It goes for 10 years with the possibility of renewal for another five?

Masakazu Aono: Yes. Of course, I have very nice colleagues at NIMS, and I'm only one person. So, I have to decide many things, but my colleagues support me and they have nice ideas and opinions. That is very helpful for me.

PSW: Can you tell us how approaches to nanoscience are different in Japan compared to the rest of the world?

Masakazu Aono: I'm not sure if this is right, but...we Japanese like to analyze materials. Japan has been strong at electron microscopy for a long time, and also optical spectroscopy. And theory, too. So, Japanese like *analysis*, to see a small path.

But, we have to develop novel materials on the basis of analyses. That path is not necessarily strong here.

PSW: I come to Japan frequently, and one thing that I notice is that people *know* about nanoscience. I met an accountant at a train station in the mountains, and he knew about experiments that *we* had done. That's a goal in America! How do we educate the public, get them interested in science in general, and nanoscience in particular? How does that happen here?

Masakazu Aono: That is related to the pragmatism of the United States. People in the United States like science, to use the science for some actual application. Japan has good industry; nevertheless, people *like* basic science. And people think engineering is a little bit dry, as compared to science, like in England. But in the United States, engineering is highly considered. Don't you think so?

For example, in the case of space development, many scientists in Japan say that it is of no use to send man to the

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moon. Why don't we send a high-performance machine there? But I always say that that is wrong. We have to send a real man to the moon, and Mars. So in that sense, the United States is great.

PSW: That's a perfect example, because for many years, the space program has caught the public imagination in America. People are familiar with telescopes, what the universe looks like. And yet, what is right in front of us at a very small scale or what is underneath the ocean, those are much less familiar, and in some ways perhaps less interesting to a lot of people.[19]

Masakazu Aono: That effect is huge, and encouraged projects at all levels and young kids in all kinds of technology.

PSW: Maybe the public support for science in Japan enabled the centers that you and Tohoku have in a way that might be a bigger challenge in America.

Masakazu Aono: Yes, that matters.

PSW: What about young scientists in Japan?

Masakazu Aono: In Japan, young [researchers] are not so active, not so aggressive. For example, young Japanese scientists don't want to be in foreign countries to have international experience or to have international discussions with scientists in different cultures, because they are wealthy enough and don't like serious things. It is a little bit harder to live in foreign countries, using a foreign language with their family. So, they are satisfied to be in Japan. I'm very much interested in fostering young scientists. So, in MANA,[2] we have two purposes: one is to make good, high-level research; the other is to foster young scientists.

We made a system called "MANA Independent Young Researchers". We selected 12 researchers right now. We pulled them from their bosses, and said, "You don't need to write papers with that boss", and "you should think of them as a mentor, or advisor". I asked the bosses at that point, and all of them agreed. So, when the boss agreed, I pulled the young scientists.

PSW: Did anyone refuse?

Masakazu Aono: Yes, two young scientists said, "I don't want to be independent."

PSW: That is a revolutionary system for Japan.

Masakazu Aono: In your country, young scientists are all independent. That makes a nice scientist, very active.

PSW: Do you have advice for young scientists?

Masakazu Aono: A young scientist should be independent in his thinking, in his way of thinking.

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

— Paul S. Weiss, Editor-in-Chief

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