When I first joined The Institute in September 2001, my research interest lay in very fundamental physics and optics research. At the time, I was mostly involved in understanding fundamental interactions of femtosecond laser pulses with matter. My initial research focused on two directions: one was to study how atoms and molecules respond to strong laser fields, while the other was on laser interactions with metals. Years later, the fundamental nature of my research in atoms and molecules remain unchanged, but my work on metals took a very unexpected turn.

In the early 2000s, the study of femtosecond lasers interacting with materials seemed to stagnate.

Many people were excited about micromachining using femtosecond lasers to make microstructures with high precision. These research activities were supported by the prevailing theory at the time—i.e., femtosecond laser pulses were so short that when an intense pulse was applied to a material, all the pulse energy would be used for material ablation and virtually no energy deposited into the material. With this prevailing theory, people also argued that femtosecond laser ablation was very efficient since little heat was involved. This theory seemed to agree with the micromachining results people obtained using femtosecond lasers. Therefore, there was a sense that the theories were in place and there was not much to be done to further improve our understanding of femtosecond laser material interactions. However, one surprising fact was that the prevailing theory was never fully tested experimentally. Nevertheless, it was not considered to be a significant issue; since the theory was very reasonable, few thought there was need for experimental validation.

The lack of direct experimental support to the prevailing theory was also due to significant experimental challenges. To measure how much pulse energy is deposited into a metal during laser ablation, one would need to rely on subtracting the
reflection from the incident beam energy. This would work well if the metal surface is smooth and reflects like a mirror. However, for intense laser ablation, the metal surface will be damaged and diffuse light. Since it was nearly impossible to effectively collect all the diffused light, no one would have bothered to study this energy absorption issue experimentally as the theory simply made sense. Unfortunately, as I will discuss below, the prevailing theory was not as robust as it sounded.

In the first few years after I arrived at Rochester, I was joined by Anatoliy Vorobyev, a very passionate and experienced researcher who had studied longer pulsed laser phenomena but not femtosecond lasers. Anatoliy and I started to look into this femtosecond laser energy deposition problem, and we decided to build a laser calorimeter that could allow us to make direct measurements. It took a great amount of work to get this calorimeter built and with it, we performed the first calorimetry studies in femtosecond laser interactions. What we found was quite astonishing; instead of seeing little pulse energy deposited into the metal following femtosecond laser irradiation, we found a significant amount of energy stayed in the irradiated samples under certain experimental conditions. Although these results were very significant fundamentally, they were quickly overshadowed by some more applied findings that followed. That was in 2005, and it was the start of an era in which we found many interesting things from plain metals.

With the insight gained from studying the energy deposition, we realized that we could dramatically increase the absorption of metals following femtosecond laser irradiation. As a result, we created the so-called black metal around 2005–6, when we could turn a shiny piece of metal pitch-black as seen in figure 15.1. Not only did it appear black, but the surface had also a near-perfect broadband absorption across UV, visible, and near IR. Obviously, the black metal will be useful whenever light collection is needed, such as making better thermal sensors and detectors. Unlike black paint or coating, the enhanced absorption from our black metal came from a range of morphological micro- and nano-scale structures formed by femtosecond laser irradiation. These structures are very tiny so that the metal surface is still smooth to the touch, but can be seen under high-power microscopes. This is unique because the blackened surface is still part of the metal and retains the same metallic properties. When our invention somehow became public knowledge, the phone calls came in from businesses, fellow scientists, and people from all walks of life. As a scientist, it was an interesting experience to relate my research to the general public. But at the same time, it was also quite distracting. Little did I know that this was just the beginning of our research reaching people far beyond the academic community.

After the black metal work, Anatoliy and I were determined to push the black metal technology one step further. The black metal absorbs different colors of light undistinguishingly; we were thinking about producing a surface that would selectively absorb certain colors but reflect other colors. In that case, the metal surface would appear to be a certain color. A year later, this became a reality; we produced the so-called colored metals. At that point, we could turn shiny metals not just
black, but also different colors all through laser surface structuring. As shown in figure 15.1, we turned aluminum and platinum gold, and titanium blue. Shortly after our discovery, it was interesting to see that a New York Times article called this work “a feat of optical alchemy.” The article went on to discuss possibilities of creating colorful jewelries.

After studying light absorption, Anatoliy and I went on to study light emission from the black metal. At the time, the United States and many other countries around the world were phasing out incandescent light bulbs. There was no dispute about the low efficiency from incandescent lamps. However, one limiting factor often overlooked was that the tungsten filament, being made of a metal, has very low emittance because of its low absorbance. However, there was really nothing people could do to change this at the time because the emittance is determined by the intrinsic property of tungsten. Anatoliy and I started to discuss if we could change the emittance of the tungsten filament with our black metal technology. Experiments were tried; we fired a femtosecond laser beam directly through the glass envelope of a light bulb and blackened a part of the filament. After the blackening, the light bulb was turned back on. Lo and behold, the blackened part of the filament glowed much brighter—indeed, twice as bright! As the law had been passed and nothing could really rescue the incandescent bulbs, I could deeply feel the public emotions toward the tungsten bulb. Prompted by our discovery, the New York Times ran two separate articles on this topic: “Can Incandescent Bulbs Compete on Efficiency?” and “Incandescent Bulbs Return to the Cutting Edge.”

After much study on photons, we turned our attention to water. The question Anatoliy and I had was if our surfaces would have different wetting properties. In the next few years, we created a number of laser processing techniques that turn a wide range of regular materials, including metals, semiconductors, dielectrics, and even biological materials, superhydrophilic and superwicking. Compared to other hydrophilic materials, the hydrophilicity we created is extremely strong. Water or other liquids, as soon as they touch the bottom of a vertically standing treated surface, will defy gravity and sprint uphill at a high velocity (several centimeters per second). One potential use of this technology is for liquid cooling, particularly in microelectronics as heating is a major issue. After we turned silicon superwicking,
from Black to Superhydrophobic

this potential application was immediately discussed in yet another Times article entitled “For Cooler Chips, Follow the Grooves.”

After the superhydrophilic work, we turned to the counterpart technology—i.e. creating a superhydrophobic surface with femtosecond lasers. A few years later, we produced a multifunctional surface that is both black and super water repellent. In fact, the superhydrophobic surface we created repels water with such a vigor that water droplets bounce off like Ping-Pong balls. One interesting fact is that most scientific discoveries in physics are driven by pursuing high tech. But in contrast, our work in creating superhydrophobic surfaces was actually driven by an ongoing project we have working with the Bill & Melinda Gates Foundation. For this project, we planned to develop a self-cleaning surface to address global sanitation needs. Today, our Gates Foundation project has entered a new phase with a close collaboration with Changchun Institute of Optics, Fine Mechanics, and Physics (CIOMP) in China.

My collaboration with CIOMP started in 2016. CIOMP is the first optical institution in China, in a similar position as our Institute in the United States. Given the positions that each institute holds, giving birth to the academic study of optics in their respective countries, CIOMP and the University of Rochester had been keen to establish a close collaborative tie. In fact, several rounds of high-level institutional meetings and visits were carried out by the administrators from both sides. From the Rochester side, this included Provost Peter Lennie, the then-Dean of Hajim School Robert Clark, and Vice Provost Jane Gatewood of Global Engagement. With
CIOMP, an institutional MOU was signed by Provost Lennie and a departmental exchange MOU was signed by The Institute director, Xi-Cheng Zhang. In 2015 and 2016, the CIOMP leadership again visited UR and discussed building a more concrete collaboration. With strong support from Director Zhang and the current dean of the Hajim School Wendi Heinzelman, a close collaboration was established between my lab at The Institute and a newly established Photonics Lab at CIOMP. I have been able to oversee the design and growth of this new lab. Merely two years later, starting from a completely empty space and a couple of part-time staff helpers, the new CIOMP Photonics Lab has rapidly grown into a team of about sixty members housed in a 30,000-square-foot state-of-the-art modern research building. The lab research covers areas of laser-matter interactions, high-order nonlinear optics, materials and devices, and nanophotonics. Many of my Rochester lab members have also contributed to the close interactions with the CIOMP lab, including Subhash Singh, Mohamed Elkabbash, Jihua Zhang, Kwangjin Lee, and Kai Davies. The CIOMP lab also provided summer intern opportunities to a number of Rochester graduate and undergraduate students, including Bo Lai, Cong Cong, Xiaoyun Li, and Huiyan Li. Not only did the CIOMP lab make great strides in building its team, scientific research, and infrastructures, but it also built these on a firm ground in inclusiveness and diversity. Today, over half of the CIOMP lab staff members are foreign nationals, and more excitingly, our student body consists of more than 50 percent females, a ratio rarely seen anywhere in the world for a STEM program. Apparently, my Rochester and CIOMP labs have plenty to learn from each other. More importantly, the current ongoing Gates Foundation project funds the two labs working side by side to scale up our functionalized materials and bring them to real-world sanitation applications.

Figure 15.3 and 15.4. Laser-treated surfaces become both pitch-black and (left) superhydrophilic: a water droplet sprints upward against gravity on a superhydrophillic surface; (right) superhydrophobic: a water droplet is repelled off a superhydrophobic surface. Photo by J. Adam Fenster/University of Rochester.