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EDITORIAL

Moore icon: an interview with Prof. Hanming Wu – challenges and opportunities in the post-Moore era

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Wu Hanming is a distinguished academician at the Chinese Academy of Engineering, renowned for his expertise in microelectronics technology, specifically integrated circuit (IC) manufacturing. He currently serves as the dean of the College of Integrated Circuits at Zhejiang University. Throughout his career, he has been at the forefront of China's IC chip industry and has played a pivotal role in the research and development (R&D) of large-scale production process technology for seventh-generation chips. Notably, his contributions include the successful use of a theoretical model to support the R&D of China's first large-scale production plasma etching machine. He has also facilitated the establishment of a common platform for designing intellectual property (IP) core technology, which has fostered the coordinated development of the chip manufacturing industry chain. His exceptional work in this field has been recognized by prestigious universities worldwide, as his non-equilibrium low-temperature plasma hybrid model/overall model has been incorporated into textbooks as a valuable teaching resource. In addition to his achievements in IC chip technology, he has served as the chief scientist for "quantum dot memory and magnetic memory technology research and development." His extensive research output comprises 116 published papers and 67 authorized inventions. As the project chief, he has garnered numerous accolades, including four first prizes at the provincial and ministerial levels, as well as three second prizes for national scientific and technological progress. In 2014, he received the distinguished title of " Best National Excellent Scientific and Technological Worker". Moreover, Wu Hanming has held the position of chairperson at the esteemed "China International Conference on Semiconductor Technology" (CSTIC).

1. At present, it is unlikely that semiconductor technology will be driven by miniaturizing complementary metal-oxide–semiconductor (CMOS) transistors alone. With the advent of the post-Moore era, what do you think are the main technologies that will continue using Moore's Law?

Wu: In the post-Moore era, there are four main directions shaping the IC industry.

The first direction is the "silicon-von" paradigm. Currently, the industry's mainstream technology revolves around binary-based metal-oxide semiconductor field-effect transistors (MOSFETs) and traditional planar CMOS, as well as more advanced pan-CMOS technologies such as stereogrid fin field-effect transistors (FinFETs), ring-grid nanowire field-effect transistors (NWFETs), carbon nanotube field-effect transistors (CNTFETs), and other similar technologies. The second direction is the silicon-like model, which includes architectures like negative capacitance field-effect transistors (NC-FETs), tunneling field-effect transistors (TFETs), phase-change field-effect transistors (FETs), single-electron transistors (SETs), and other non-CMOS approaches focused on charge transformation. This model is the main technology route for continuing the advancements of Moore's Law. The third direction is the brain-like paradigm. This approach involves emulating neural behaviors to enable parallel computing and memory tasks with low power consumption. This will underlie. It holds great promise for the development of artificial intelligence and offers exciting prospects for various industries. The fourth direction is the emerging paradigm. This includes state transformation, where information is strongly correlated with electronic states and spin orientation. It also encompasses

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new device technologies such as spin devices and quantum technologies, as well as emerging architectures like quantum computing and neuromorphic computing. However, these advancements are primarily in the realm of fundamental research, and it may still take a decade or more before large-scale industrial applications become a reality.

2. Can you analyze the current IC manufacturing dynamics in China?

Wu: Over the years, China has maintained a prominent position in the import of integrated circuits (IC), indicating a strong demand for chips in the Chinese market. It is undeniable that the semiconductor industry's growth relies heavily on the Chinese market. Consequently, I firmly believe that globalization will inevitably make a comeback.

As far as chip manufacturing is concerned, there is currently a strong emphasis on advanced technology and processes. For example, establishing a 14-nm (nm) production line with a capacity of 20,000 units per month would require an investment of approximately 1 billion Chinese yuan (RMB). This substantial investment poses a challenge for average small and medium-sized enterprises that may struggle to afford it. Furthermore, as the capital requirements increase, the overall production speed becomes slower, while costs rise exponentially. In the case of advanced manufacturing, high research and development expenses, as well as construction costs, have impeded the pace of factory construction.

3. What do you think is the current global situation of the industry?

Wu: The United States has a dominant position in software-related equipment data acquisition (EDA) and intellectual property (IP), holding a substantial 70 percent share in these fields. It also has a significant presence in the logic and discrete devices. In contrast, East Asia, particularly China, leads the global market in memory. The United States, Japan, and Republic of Korea enjoy considerable advantages in semiconductor equipment, while its role in material parts is relatively minor. Furthermore, mainland China holds significant influence in packaging testing, with the entire region monopolizing the global market in this area.

These dynamics underscore the global nature of the semiconductor industry. However, the United States is currently experiencing a trend towards insourcing. It is important to note that data analysis suggests that if the United States pursues an independent complete industrial chain, it would not only require substantial investments but also lead to a significant increase in overall product prices.

4. You mentioned that China's IC industry is facing great challenges, including that the industrial chain is too long and too wide. What do you think are the central challenges of current chip manufacturing in the post-Moore era? Additionally, what do you think is the greatest problem facing our domestic IC industry?

Wu: The primary challenge lies in achieving precise patterning. Currently, the leading advanced process relies on a 193-nm wavelength light source to expose graphics between 20–30 nm in size. However, when the wavelength is significantly larger than the physical dimensions, it results in a degradation of resolution.

The major challenges in chip manufacturing revolve around the adoption of new materials and processes. With 64 emerging materials supporting the advancement of Moore's Law, the industry must constantly innovate and implement these materials to drive technological progress. Without the integration of new materials, performance improvements will stagnate, impeding the industry's ability to meet evolving demands.

The paramount challenge in chip manufacturing is enhancing yield. Yield enhancement is the most difficult and persistent headache for chip companies, as the manufacturing process accumulates a significant number of statistical defects. Without significant improvements in the yield rate, any progress made cannot be regarded as a true success.

In the post-Moore era, the IC industry requires three key drivers, eight technical aspects, and four power-performance-area-cost (PPAC) goals.

However, the main challenge for the industry lies in the insufficient development of an engineering culture. China made significant progress in addressing a biased scientific orientation by successfully researching its first silicon single crystal in 1958, although it was six years behind the U.S. and two years ahead of Japan in terms of original innovation. Despite economic limitations, this scientific breakthrough placed China ahead globally. However, as the industry expanded and production capacity increased, China gradually fell behind other countries primarily due to an excessive focus on pure scientific principles and neglecting engineering science. It is important to note that China did not start late in the semiconductor field, but the gap can be attributed to the lack of emphasis on nurturing an engineering culture. Chip manufacturing is not solely about scientific breakthroughs and original research problems; it relies fundamentally on systematic engineering advancements and breakthroughs.

5. What other suggestions do you have for the innovative development of China's IC industry?

Wu: The development of China's IC industry is currently facing significant challenges, mainly due to the complexity of the industrial chain and the difficulty in achieving excellence in every stage. Given the intricate global situation, it is crucial for us to be resolute in our development efforts and leverage our internal strengths. We should prioritize the concept of double-cycle development, with a particular focus on enhancing the internal cycle, while also maintaining an open-minded approach to support global progress.

In light of this, I propose the following four recommendations for the field of chip manufacturing: Firstly, we should capitalize on the achievements of national major special projects and continue to offer strong support for the R&D work on advanced processes. Additionally, we should prioritize the development of special processes and the various links within the related industrial chain. Secondly, it is essential to adhere to an industry-oriented technology route. By doing so, we can align our technological advancements with the needs and demands of the industry, ensuring their practical and effective implementation. Thirdly, we need to maintain strategic determination and steadfastly follow the path of self-reliance, self-improvement, and openness to the outside world. This approach will enable us to develop our capabilities independently while also fostering collaborations and mutually beneficial partnerships with global stakeholders. Lastly, establishing a comprehensive public technology platform capable of integrating design and manufacturing processes will be crucial. Such a platform will facilitate seamless collaboration between academia, industry, and research institutions, thereby promoting efficient knowledge sharing and innovation.By implementing these recommendations, we can address the current challenges in the IC industry and pave the way for sustainable and robust development in China's chip manufacturing sector.

6. Based on its current circumstances, what are the weaknesses of IC industry talent? What are the strengths?

Wu: In the next three to five years, talent shortage is expected to become the norm, not just in our country, but globally. The rapid development of the industry has outpaced the ability of universities and educational sectors to produce skilled professionals in a timely manner. As a result, enterprises will increasingly need to take on the responsibility of cultivating talent themselves.

However, there are also advantages to leverage. For instance, our country has a higher number of science and technology graduates compared to all of Europe. This provides a strong foundation to meet the demand for talent in the IC industry chain. Nevertheless, the IC industry chain is extensive, encompassing various fields such as materials, physics, machinery, and computers. Enterprises often face challenges when hiring graduates who lack practical experience. Hence, the situation presents a dual challenge: a significant number of graduates struggle to find employment while enterprises urgently require immediate-ready talent.

Overall, it is evident that the global talent shortage is a complex issue driven by the rapid pace of industry growth and the mismatch between education and industry needs.

7. What is the difficulty of talent cultivation? What should we pay attention to?

Wu: One of the major challenges our country faces in cultivating talent with IC expertise is the lack of up-to-date teaching materials, particularly textbooks. In the rapidly evolving IC industry, new-generation products emerge approximately every two years, with constant advancements and innovations arising every 18 to 24 months. Unfortunately, our textbooks often become stagnant, sometimes remaining a decade or more behind the current industry developments. This creates a disconnect between universities, their teaching materials, and the industry's progress. As a result, graduates are not adequately equipped to meet the evolving demands of the industry.

Numerous academics have expressed the view that Integrated Circuits (ICs) have yet to be recognized as a first-level discipline. Consequently, there is a limited availability of slots for master's and doctoral degree programs in this field. This means that university students are primarily allocated based on second-level disciplines, resulting in a significant scarcity of opportunities for those interested in pursuing IC-related studies at the university level.

Furthermore, the development of the IC industry is a gradual process. The research and development of a chip go through multiple iterations and require long-term support. Using an analogy, the support for ICs is not akin to a "double-explosion firecracker" that has a brief rise due to the initial explosion and then quickly fades away without a subsequent explosion. Instead, it should be likened to a three-stage rocket, where each stage propels it further into orbit gradually and systematically.

8. How can the bottleneck of talent be solved by opening up the channels of industry, academia and research?

Wu: Many talented individuals are employed by companies but may lack practical experience, hindering their immediate contribution. Opening up channels of communication and collaboration between industry, academia, and research can offer a viable solution to this issue. Taking inspiration from practices in the United States, we can strengthen the cooperation between universities' scientific research efforts and industry. During my time at the University of California, Berkeley, I participated in projects alongside leading enterprises. In this model, enterprises provide the projects, while universities contribute their expertise to complete them. In China, where many businesses struggle financially, the government can potentially implement preferential policies to support the cultivation of specialized talent.

9. What was your aim in starting this journal?

Wu: The IC industry is a strategic and market-driven sector characterized by the convergence of national strategy and market dynamics. It requires continuous advancement in technology, significant capital investment, and a unique blend of pioneering technology and application-oriented innovation. Our goal is to establish a bridge that connects fundamental research with practical engineering, creating a first-class journal called *Moore and More* that is embraced by international scientists and engineers. Through this journal, we aim to promote collaboration between education, industry, and research while fostering robust international academic communications. We also seek to create a "Beyond Moore" community and accelerate the transformation of scientific and technological achievements.

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Declarations

Competing interests The authors declare that they have no competing interests.

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Mengjiao Li Dr. Mengjiao Li is a distinguished doctoral supervisor, acclaimed as a National High-level Young Talent and Shanghai's Leading Talent for Overseas Youth. Between 2019 and 2022, she embarked on postdoctoral research endeavors across China, Taiwan and at the University of Southern California, USA. Dr. Li's research is centered on advancing the capabilities of novel post-Moore's law micro/nano semiconductor optoelectronic devices, alongside pioneering developments in sub-nanometric integrated logic circuits, memory storage, and smart sensory electronic chips.

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