Synchrotron Virtual Laboratory for the Semiconductor Industry

Conforming to Moore's law, the minimum line width of an advanced semiconductor device will decrease to 10 nm within a few years. The semiconductor industry is now highly technological and intensive of capital; the global competition between companies is fierce. Only three major semiconductor companies—Intel (US), Samsung (Korea) and TSMC (Taiwan)—survive in this battle. In 2014, the value of the output from Taiwan's IC industry exceeded 2,000 billion NT dollars, about 5.5% of the gross domestic product of Taiwan. Maintaining the semiconductor industry flourishing has obviously a direct impact on Taiwan's society in a positive way.

Hsinchu Science Park is the heart and engine of the semiconductor industry in Taiwan. There are many industries, national labotories and universities in this integrated campus of science and technology. Located in this science park, the NSRRC has been established for more than 20 years and has developed many advanced scientific techniques, but the interaction between the NSRRC and semiconductor companies has been still small and dispersed. To promote techniques involving synchrotron radiation (SR) to key semiconductor companies, the NSRRC proposed at the end of 2013 a project named *Synchrotron Virtual Laboratory* to TSMC. It is basically an analytical platform for professional, efficient and cost-effective service, as shown in Fig.1. The major principles follow.

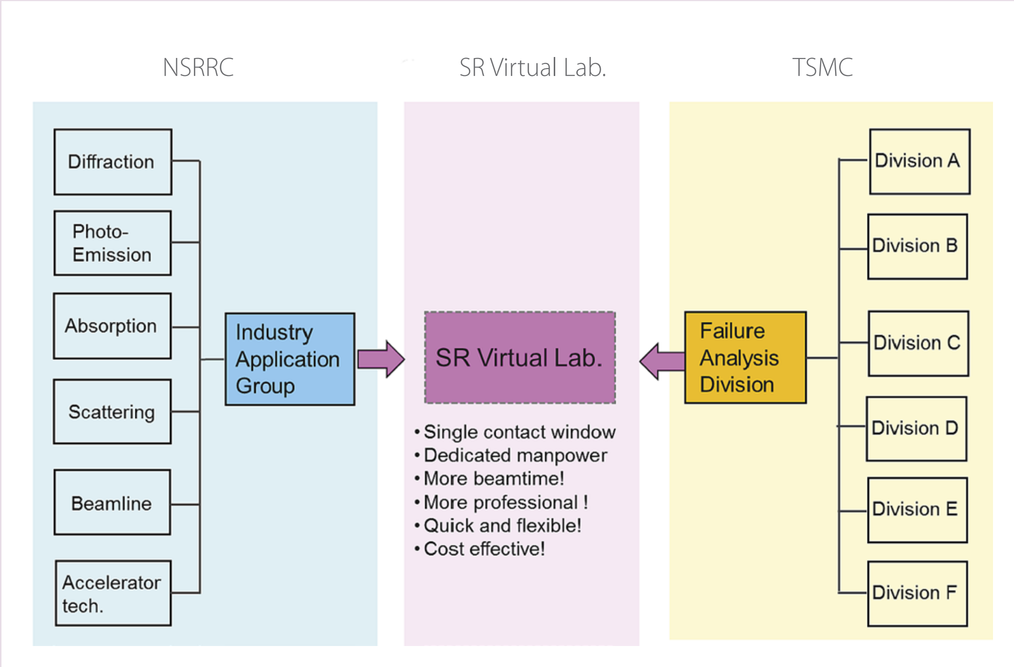

Fig. 1: Schematics of the SR virtual lab project.

1. A single contact window: TSMC has many divisions; the proposed analytical items from TSMC are diverse. To manage the analytical requests in an efficient way, we agreed to establish a single contact window on each side. The two contact windows are Failure Analysis Division (FAD) at TSMC and Industry Application Group (IAG) at the NSRRC. Based thereon, IAG will assist to integrate the resources and technology of the NSRRC to meet the requirements of TSMC. Similarly, FAD will promote SR techniques and integrate the analytical requests inside TSMC.
2. Dedicated manpower: In this project, we assign and hire dedicated personnel to treat TSMC cases. All discussion, requests and experiments related to the analytical cases thus can be followed and integrated, resulting in a professional and efficient scheme.
3. Cost-effective: In this project, TSMC hired personnel to collect and to analyze data; they can thereby use the synchrotron facilities in a more cost-effective way.

A snchrotron is a precious light source for the analysis of chemical and biological substances and materials. Academic users normally apply for beam time a few months before their experiments, but this duration is impractical for industry that must solve problems rapidly from both a production line or R&D work. Synchrotron facilities must have a versatile response for industrial users.

Based on this project, the NSRRC could allocate more beam time and arrange the beam time more frequently. This procedure would decrease the response interval and increase the flexibility of analytical work. Moreover, all NSRRC experts can join a discussion and help to solve the problems, thus providing a more professional and accurate answer to the industry. The side effects of this cooperation projects will facilitate a greater use of synchrotron techniques by industrial engineers.

This project has performed appropriately according to the idea of *Synchrotron Virtual Laboratory* since the end of 2013. The analytical requests from TSMC are diverse, but the techniques fall into three categories—measurements with X-rays (44%), photoemission (43%) and extreme ultraviolet light (~13%, excluding beam time in a separate EUV project). The beamlines most used are 24A1, 07A1 and 08A1. The contact persons from both sides worked increasingly intensively because TSMC found that synchrotron techniques revealed information inaccessible from in-house techniques. The synchrotron facilities provide information complementary to techniques involving a transmission electron microscope, giving a clear picture of the structure on an atomic scale. These efforts have helped TSMC to solve critical problems in their mass-produced devices.

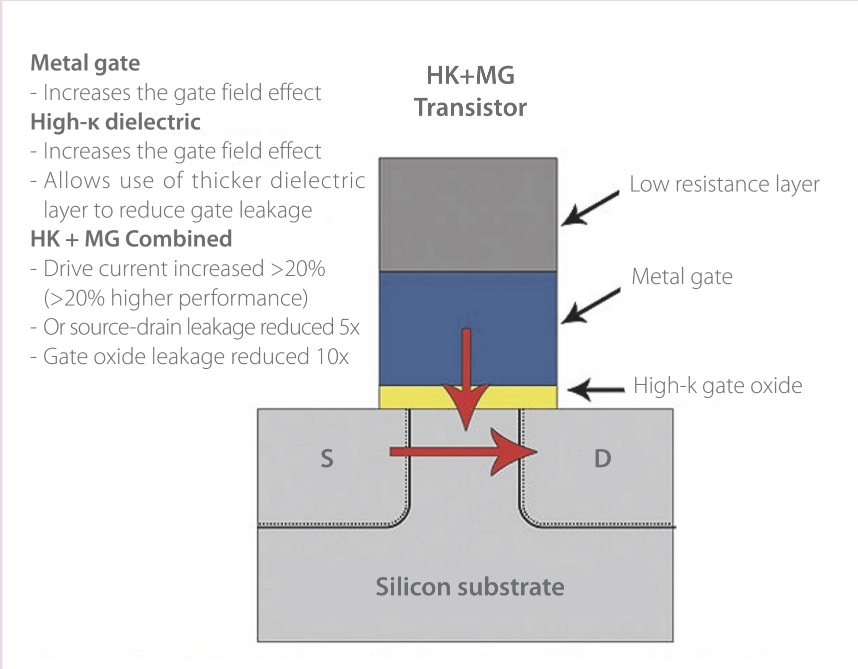

Fig. 2: Schematic diagram showing the transistor layer structure with high-κ (HK) gate oxide and metal gate (MG).

One successful case is the characterization of high-κ material in nano devices. Silicon dioxide has served as a gate oxide material for decades. As transistors have decreased in size, the thickness of the SiO_2 gate dielectric has steadily decreased to increase the gate capacitance and thereby drive current. As the thickness scales below 2 nm, leakage currents due to tunneling increase greatly, leading to a large consumption of power and decreased device reliability. As illustrated in Fig. 2, replacing the gate dielectric of silicon dioxide with a high-κ material, such as hafnium dioxide, hafnium silicate or zirconium silicate, allows an increased gate capacitance without the associated leakage effects.

The deposited high-κ dielectric layer suffers from various thermal and plasma processes during fabrication of a chip. Various defects such as vacancy or interstitial atom are generated via diffusion or ion bombardment, which result in current leakage. Characterizing the material properties of the buried dielectric layer of high-κ is hence important in fabricating advanced nano devices. Companies have traditionally used an in-house technique involving X-ray photoelectron spectra coupled with ion sputtering to reveal the depth profile of the composition in the layered structure, but the original composition of the material becomes disturbed as the sputtering yield of elements varies greatly, thus yielding an incorrect result. In contrast, photoelectron spectra with highly brilliant synchrotron radiation and tunable energy can serve to explore the chemical binding and electronic properties in a buried layer or interface. With the advantage of great resolution of energy, overlapping signals become resolved. One can tilt the sample to capture and to analyse the excited electrons from various depths without destroying the specimen. The synchrotron radiation photoemission technique thus provides useful information to reveal a clarified picture of the atomic structure inside the nanometre devices.

This project was initially applicable for only 17 shifts of beam time, but eventually used more than 40 shifts because SR techniques enabled solutions of critical problems. The products thereby acquired increased competitive strength in the world. In consequence, TSMC has proposed a project for 2015, to increase the applied beam time to more than 120 shifts. The NSRRC conducts projects from various other industries, including pharmaceutical, semiconductor, green energy, medical therapy and microsystems, and promotes the use of SR techniques for the steel and petroleum industries. We contend that a synchrotron is not only a probe unique for scientific research but also a new vision for industry. (Reported by Bor-Yuan Shew)