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A Review of Optomechatronic Ecosystem

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***Abstract*— The landscape of optomechatronics is viewed along the line of light vs. matter, photonics vs. semiconductor, and optics vs. mechatronics. Optomechatronics is redefined as the integration of light and matter from atom, device, system to application. The markets and megatrends in optomechatronics are further listed. The author then focused on optomechatronic technology in semiconductor industry as example and reviewed the practical systems, characteristics, and trends. Optomechatronics together with photonics and semiconductor will continue producing the computational and smart infrastructure required for the 4th industrial revolution.**

***Index Terms*— Photonics, semiconductor, optomechatronics, 4th industrial revolution.**

I. INTRODUCTION

OPTOMECHATRONICS is the fusion of optics and mechatronics with system thinking. Optomechatronics emerged as a prominent trend in system integration in later 1990s and early 2000s [1]-[9]. Optomechatroncis is multidisciplinary, integrative, and synergetic in nature. The development of optoelectronic product or system involves many science and engineering fields. Optomechatronics is multifaceted according to different points of view such as:

- optics vs. electronics vs. mechanics
- device vs. system vs. application
- hardware vs. software vs. AI
- human vs. machine vs. environment

There are various approaches to understand optomechatronics according to individual background and emphasis. In this paper, the author provides a simple holistic view to describe the landscape of optomechatronics. It is dynamic and covers the entire optomechatronic ecosystem.

II. OPTOMECHATRONIC LANDSCAPE

The landscape of optomechatronics is illustrated along the views of light vs. matter and device vs. system in the vertical and horizontal directions respectively, as shown in the figure 1.

A. Light vs. Matter

In classical physics, the light is modeled as electromagnetic wave and the matter as continuous medium. The interaction of light and matter is passive through diffraction, interference, polarization, reflection, and refraction.

In quantum physics, the light is modeled as photon and the matter as electron, atom, molecule, and crystal lattice (phonon). The interaction of light and matter is active through emission and absorption.

The spectrum of light not only includes IR/Visible/UV but also extends to microwave photonics/THz optics and X-Ray/Gamma-Ray.

The state of matter not only includes solid/liquid/gas/plasma but also covers vacuum/surface/interface.

B. Device vs. System

A device refers to a product manufactured with micro or nano technology, and it has at least one feature dimension at micro/nano/atomic scale.

A system refers to a product manufactured with assembling technology, and it has the feature dimensions at macro scale.

C. Photonics vs. Semiconductor

Photonics involves generation, transmission, and detection of photons. Photonic devices include light sources, microstructured optics, and light detectors.

Semiconductor involves manufacturing of microstructures using semiconductors as well as conductors and insulators. Semiconductor devices include the various microelectronic components (CPU/GPU/TPU, memory, ASIC, MMIC, power), MEMS, and photonic semiconductor devices.

Photonic semiconductor is the fusion of photonics and semiconductor. Photonic semiconductor devices include the conventional optoelectronic devices such as emitters (LED/Laser), detectors (PD/PTX/PIN/APD/SiPM), and imaging sensors (CCD/CMOS), and more recent developments in silicon photonics, photonic integrated circuits (PICs), and optical MEMS (MOEMS or micro-optomechatronics).

D. Optics vs. Mechatronics

Optics is to study the behavior of light. The optical functions range from illumination and detection, optical metrology, machine vision, material processing and actuating, optical data storage and display, to optical data transmitting and computing.

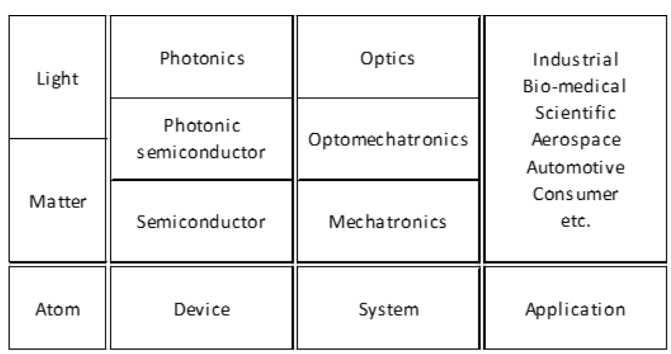

Fig. 1. The landscape of optomechatronics

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The optics is non-contact, non-invasive, EMI-insensitive, high in dynamic range, ultra-precise, high speed, low power consumption, and parallel processing in nature.

Mechatronics is to study the integration of mechanics and electronics with system thinking. The mechatronic functions range from sensing, actuation, information feedback, motion/state control, to computation.

Mechatronics has two aspects: mechanics serves electronics, and it provides the physical structure for electronic devices and systems; and electronics serves mechanics, and it provides feedback and control to mechanical devices and systems.

E. Market and Application

Optomechatronic technology has wide range of applications from industrial, scientific, bi-medical, aerospace, automotive, to consumer markets.
Examples:

- Industrial: EUV photolithograph system
- Scientific: LIGO gravitational-wave observatory
- Aerospace: JWST space telescope
- Biomedical: robotic surgery
- Automotive: autonomous driving
- Consumer: 5G/6G mobile communication

In light of the new ecosystem, optomechatronics is redefined as the integration of light and matter from atom, device, system to application.

F. Megatrends in Optomechatronics

The future of optomechatronic technology will expand:

- from visible, IR, and UV spectrum to microwave photonics/THz optics and X-Ray/Gamma-Ray
- from micro to nano to picometer precision
- from continuous to quantum world (single photon/electron/atom/molecule)
- from serial to parallel to quantum computation
- from semi-autonomous to full-autonomous system
- from machine vision to artificial intelligence
- from traditional to new materials, devices, systems, and applications
- from niche to ubiquitous and green

An optomechatronic system is application specific, and each product has its unique characteristics according to the requirements on computational power, machine-environment interaction, and human-machine relationship.

II. Optomechatronics in Semiconductor Industry

The semiconductor manufacturing is one of most demanding industrial applications for optomechatronic systems in terms of precision, speed, and intelligence achieved in well controlled environments. There are many practical optomechatronic systems in semiconductor fabs.

A. Optical Methods in Semiconductor Manufacturing

Optical methods are widely integrated into semiconductor tools and processes. They spread in cleanroom from front-end to back-end to assembly-test. They can be broadly classified as two categories: fabrication and metrology, as shown in the tables I and II.

TABLE I
OPTICAL METHODS FOR SEMICONDUCTOR FABRICATION

area	key process	optical methods for fabrication
front-end	photolithography	light sources (DUV/EUV) for exposure
	diffusion	gas immersion laser doping (GILD)
	rapid thermal processing (RTP)	IR lamps as heat sources
back-end	mount/demount	UV releasable tape
		laser releasable temporary bonding
	die separation	laser stealth dicing
	Die-sorting	machine vision in die-sorting
assembly-test	die-attach	machine vision in die-attach
	wire-bonding	machine vision in wire-bonding
	soldering	IR lamp/laser as heat sources
	alignment and quasi-hermetic seal	UV-cured adhesives
	hermetic seal	laser welding

TABLE II
OPTICAL METHODS FOR SEMICONDUCTOR METROLOGY

area	key process	optical methods for metrology
front-end	wafering/epi growth	XRD for crystal structure
		photoluminescence for band structure
		optical scan for wafer surface defect density
	oxidation/CVD/PVD thin films	interferometer and ellipsometer for film thickness and optical constant
	photolithography	laser heterodyne interferometer for measuring displacement
		fiber Bragg grating sensor for measuring strain and temperature
		reflectometry and scatterometry for surface profile, TTV, film thickness and CD
	dry etching	emission spectroscopy for critical wavelength
		laser spectroscopy for end point detection
	ion implementation	optical density (transparency) for monitoring doping level
	rapid thermal processing (RTP)	optical pyrometry for monitoring temperature
	optical inspection	compound microscopes
back-end	optical inspection	automated optical inspection (AOI) for wafers and chips
assembly-test	GD&T	optical CMM for measuring mechanical dimensions white light interferometry for surface roughness
	optical inspection	stereo microscopes
cleanroom	monitoring	optical particle counter
		FTIR for detecting organic film condemnation

- fabrication: to change the property, shape and/or state of material directly using photon energy (UV/IR/Laser) or assisted by machine vision.
- metrology: to inspect, monitor, and analyze the state of product, process, equipment, and cleanroom.

B. Characteristics of Optomechatronics in Semiconductor Industry

Semiconductor industry represents one of most advanced fields in the application of optomechatronic technology. The optomechatronic systems in semiconductor industry have a few unique characteristics.

1) **Perfection**

The cleanroom in semiconductor industry can provide pure environment for optomechatronic technology. It has controlled temperature, pressure, humidity, air flow, particle count, and even vacuum condition if necessary. It has reduced mechanical noise, impact, and vibration. It can also shield the EMI, light, and background radiation in extreme cases.

2) **Precision**

The optomechatronic systems in semiconductor photolithographic process and metrology are deciding factors to advance the semiconductor technology nodes from submicron to deep submicron to nanotechnology [10]-[14]. The table III shows the evolution of light sources in semiconductor lithography, and the resolutions are approximate numbers.

3) **Productivity**

The optomechatronic tools in semiconductor processes are designed for HVM (high volume manufacturing). They are highly automated and operated in matrix fashion. They can handle hundreds of wafers per day, thousands of dies per hour, and millions of devices per week.

TABLE III
EVOLUTION OF LIGHT SOURCES IN LITHOGRAPHY

light source	wavelength	start year	resolution
g-line	436nm	1982	1um or over
i-line	365nm	1990	800nm-350nm
KrF	248nm	1994	280nm-90nm
ArF	193nm	2001	110nm-28nm
EUV	13.6nm	2019	14nm or less

The precision and productivity of optomechatronic systems in semiconductor industry supported with perfect clean room environment are unmatched by other applications.

C. Trends of Optomechatronics in Semiconductor Industry

The future of optomechatronic technology in semiconductor manufacturing will go:

- from discrete function to integrated system
- from island to in-line system on production line
- from post-process to in-situ inspection and metrology
- from existing to new technologies and systems

III. RELATIONSHIP AMONG PHOTONICS, SEMICONDUCTOR AND OPTOMECHATRONICS

The relationship among photonics, semiconductor and optomechatronics is summarized in the figure 2.

Photonics has high sensitivity, high speed, and parallel processing. Semiconductor has controlled environment, high automation, and matrix processing. The combination of photonics & semiconductor supplies key components for optomechatronics while optomechatronics provides critical equipment for the photonics & semiconductor industry.

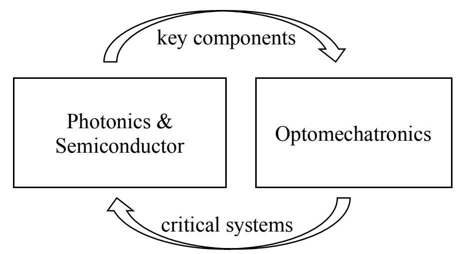

Fig. 2. The relationship among photonics, semiconductor and optomechatronics

IV. SUMMARY

Optomechatronics powered by photonics and semiconductor is multidisciplinary, integrative, and synergetic in nature. It involves many science & engineering fields and has wide applications. In this paper, the landscape of optomechatronics is illustrated along the views of light vs. matter and device vs. system. It is a simple and dynamic view extended to the entire optomechatronics ecosystem. Optomechatronics is redefined as the integration of light and matter from atom, device, system to application.

The author then focuses on optomechatronic technology in semiconductor industry as example and reviewed the practical systems, characteristics, and trends.

The combination of photonics & semiconductor supplies key components for optomechatronics while optomechatronics provides critical tools for the photonics & semiconductor industry. They work together to advance the development of new device and systems for various applications.

The semiconductor industry is the driving force for the 3rd industrial revolution. Optomechatronics together with photonics and semiconductor will continue producing the computational and smart infrastructure required for the 4th industrial revolution.

This article is a technical overview on the industrial ecosystem in optomechatronics. Any mention to specific technique, material, device, product, or market is for reference only. The perspective reflects the author's unique multidisciplinary academic background and in-depth industry experience in microelectronics, optoelectronics, and photonics. Different points of view are not only welcome but also encouraged. The interested readers can learn more about any constituent discipline or technology available in publications.

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Sam Zhang received a B. S. E. degree in Mechatronics with the highest honor and a B. S. degree in Computer Science, simultaneously from University of Electronic Science and Technology of China (UESTC) in 1990. He was the first graduate student in China majored in Semiconductor Integration Technology and had the M. S. E. degree from Southeast University in 1993. He then worked at Microelectronic Lab in Nanjing Research Institute of Electronic Technology (NRIET) for two years. He entered his Ph.D. program at University of Windsor in 1995 and obtained a doctor degree in Optomechatronics in 1999. He worked shortly as an instructor at University of Windsor and then Director of Application Engineering at CADD Edge Canada Inc. He joined Excelitas (formerly PerkinElmer Optoelectronics) in 2000. He has worked as Senior Member of Technical Staff in both R&D and NPI environments, and successfully led many programs and initiatives at Excelitas over the last 20+ years. He has published several review papers and holds several patents on integration of semiconductors and photonics. He also obtained an MBA degree in General Management from McGill University in 2006. He has been a registered member of Professional Engineers Ontario (PEO) since 1999.