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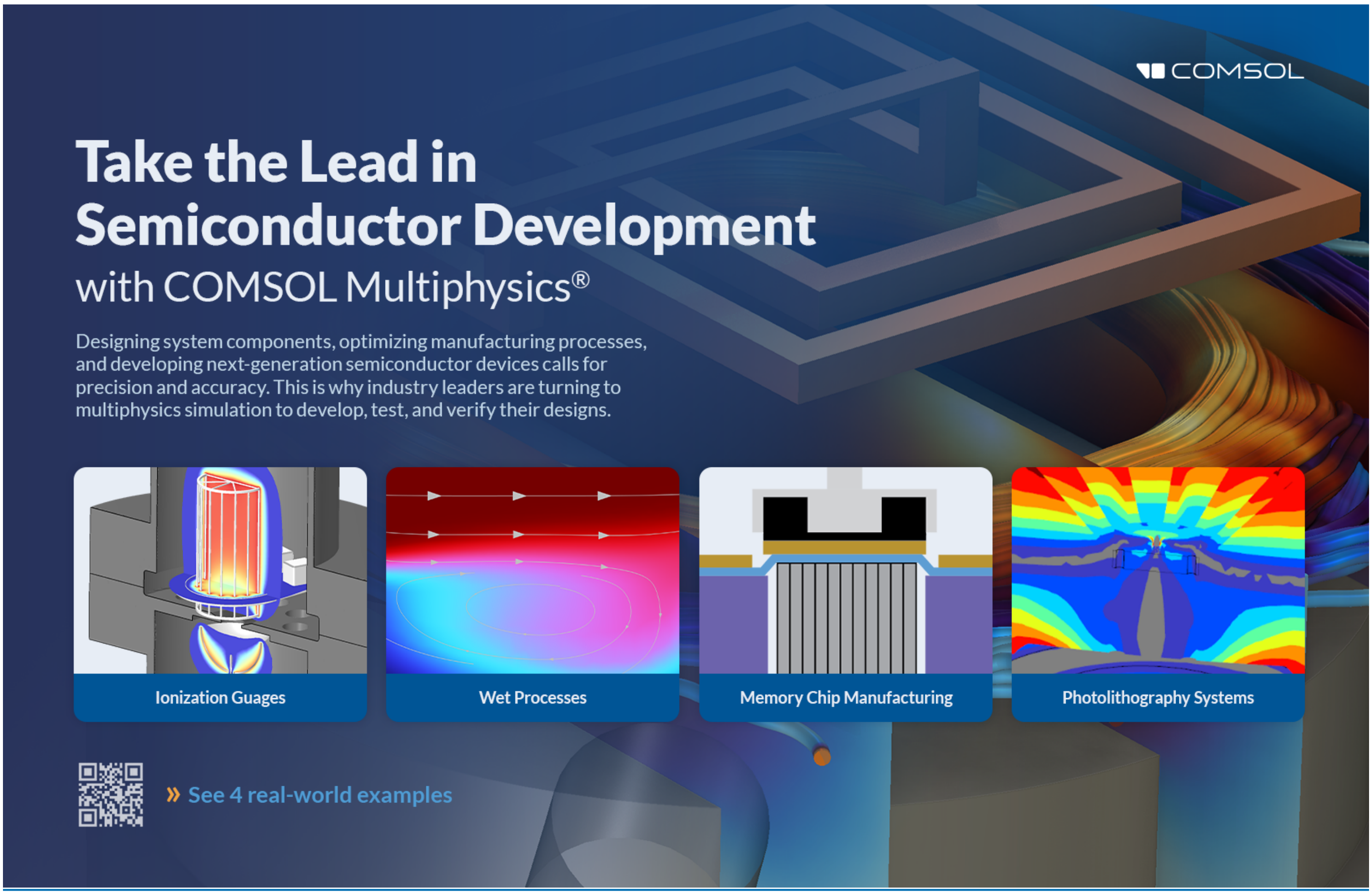

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PZT photonic materials and devices platform

Yujun Xie[1, ‡], Peng Wang[1, ‡], Hongyan Yu[4, ‡], Chengyang Zhong[1, 2, 3], Jie Peng[1, 2, 3], Jungan Wang[4], Chen Yang[4], Yu Han[5], Ang Li[1, 2, 3], Zehao Guan[1, 2, 3], Feng Qiu[4, †], and Ming Li[1, 2, 3, †]

[1]Key Laboratory of Optoelectronic Materials and Devices, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China

[2]Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100190, China

[3]School of Electronic, Electrical and Communication Engineering, University of Chinese Academy of Sciences, Beijing 100049, China

[4]Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou 310024, China

[5]Juhe Electro-optic (Hangzhou) Tech. Co. Ltd. Hangzhou 310024, China

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Ferroelectric materials are increasingly garnering substantial interest due to their potential applications in optical communication, optical computing, and sensing, among others. This surge in attention is largely due to recent advancements in the fabrication of high-quality thin films, the precision of domain engineering, and their strong compatibility with complementary metal–oxide–semiconductor (CMOS) processes. Notably, thin-film lithium niobate ($LiNbO_3$, TFLN), lithium tantalate ($LiTaO_3$), and barium titanate ($BaTiO_3$), for example, exploit the Pockels effect to facilitate highly efficient linear electro-optic (EO) modulation on chip[1–3]. The achieved ferroelectric thin film-on-insulator (FFOI) modulators can thus offer high bandwidth, low insertion loss and a linear EO response, addressing the limitations of silicon photonics (SiPhs) that rely on nonlinear plasma dispersion modulation effects. However, these materials typically face several challenges, including lower intrinsic EO coefficients (e.g., for $LiNbO_3$ and $LiTaO_3$: ~31 pm/V), complexities in fabrication and etching processes, and high wafer production costs (e.g., $BaTiO_3$ fabricated via molecular beam epitaxy)[3–5]. In recent years, thin-film lead zirconate titanate ($Pb(Zr_xTi_{1-x})O_3$, PZT) has attracted significant attention due to its high Pockels coefficient (>100 pm/V), high transparency, and superior chemical and thermal stability[6–8]. These properties confer three critical advantages[9–11]: (1) High crystalline quality and a high EO coefficient. This makes PZT an ideal candidate for high-bandwidth, energy-efficient EO modulators. (2) Wafer-scale fabrication via chemical solution deposition. This enables cost-effective, scalable production suitable for industrial applications. (3) Compatibility with CMOS processes. Deposition on silicon dioxide (SiO_2) substrates facilitates seamless integration into silicon-based heterogeneous platforms, paving the way for both advanced photonic device integration and next-generation photonic technologies.

In this work, we present a unique fabrication process to successfully produce PZT wafers ranging from 2 to 4 inches (Fig. 1(a)). Epitaxially grown PZT thin films are synthesized by combining chemical solution deposition (CDS) with magnetron sputtering. In CDS process, commercially available PZT precursor solution (Juhe Electro-optic (Hangzhou) Tech. Co. Ltd.) is utilized. The PZT solution is spin-coated on SiO_2/Si wafers, where the surface of the 5 μm-thick SiO_2 is modified by chemical treatment solutions (Juhe Electro-optic (Hangzhou) Tech. Co. Ltd.). The wafer is then annealed at around 500 °C for 30 min. Following the CDS preparation, a thick PZT layer is obtained using the magnetron sputtering technique. Through surface modification using buffer layer, we have addressed critical challenges including lattice mismatch, thermal expansion coefficient mismatch, poor adhesion, and stress relaxation between the PZT and the silicon oxide-based substrate. The integration of solution deposition and magnetron sputtering allows for the fabrication of high-quality large-area wafers with significantly reduced defects, impurities, and cracking, while enabling efficient, scalable production (Fig. 1(b)). The crystalline quality of the polycrystalline PZT thin films is characterized using X-ray diffraction (Bruker D8 Advance), with diffraction spectra recorded in the 2θ range of 20°–60°. Prominent diffraction peaks are observed at 2θ angles of 21.76° and 44.34°, corresponding to the (100) and (200) orientations of the tetragonal PZT crystal, respectively, with the (100) orientation serving as the primary diffraction peak (Fig. 1(c)). The weak peak at 2θ angles of 33.04° can be ascribed to the SiO_2 substrates. The atomic ratio of Zr to Ti in the PZT films is determined to be 52.2 : 47.8 through energy dispersive spectroscopy (EDS) analysis, which closely corresponds to the stoichiometric ratio characteristic of the morphotropic phase boundary (MPB). The refractive indices of ordinary light (o-light) and extraordinary light (e-light) at different wavelengths are measured using ellipsometry (J. A. Woollam RC2XI+). At communication wavelengths of 1310 and 1550 nm, the refractive indices of o-light are 2.405 and 2.415, while those of e-light are 2.385 and 2.395, respectively, indicating significantly reduced birefringence compared to $LiNbO_3$ (Fig. 1(d)). Leveraging the high-quality PZT thin films, we have developed a series of high-performance photonic devices that constitute our preliminary process design kit (PDK). This includes Mach–Zehnder electro-optic modulators (MZM), microring resonator modulators (MRM), multimode interferometric couplers (MMI), grating couplers (GC), and optical crossings, as depicted in the high-resolu-

Yujun Xie, Peng Wang, and Hongyan Yu contributed equally to this work and should be considered as co-first authors.

Correspondence to: F Qiu, A-photonics@outlook.com; M Li, ml@semi.ac.cn

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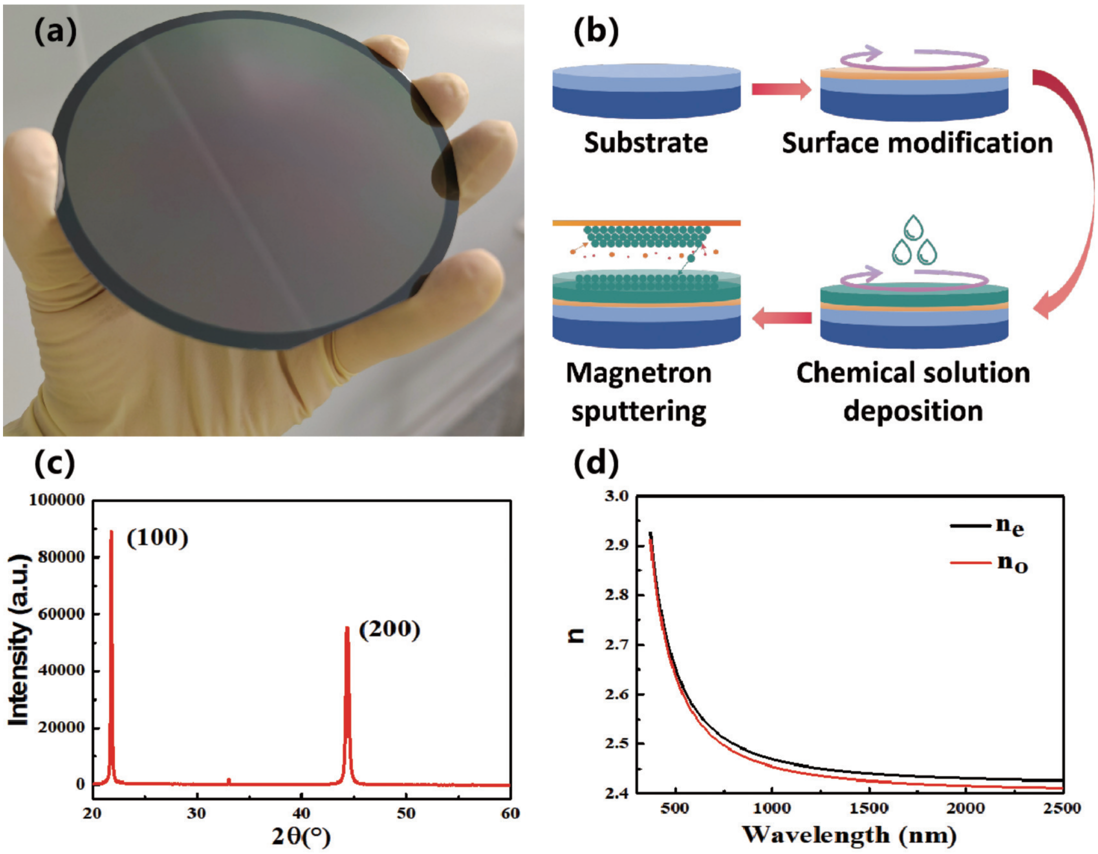

Fig. 1. (Color online) (a) Fabricated 4-inch PZT wafer. Fabrication process (b), XRD results (c) and ellipsometric measurements (d) of the PZT films.

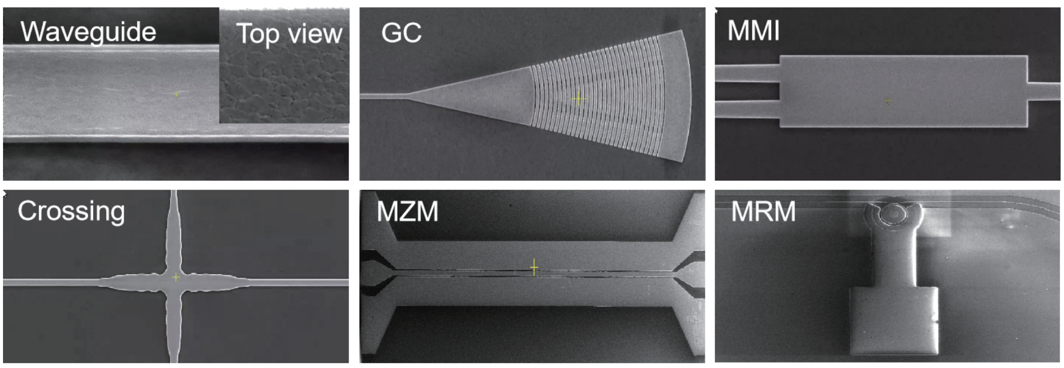

Fig. 2. (Color online) High-resolution SEM images of PZT devices.

tion images in Fig. 2. In the C-band and O-band, the optical waveguide losses are measured, yielding average values of 2.2 dB/cm for a 1 μm-wide waveguide and 2.5 dB/cm for a 0.8 μm-wide waveguide, respectively. We anticipate that these metrics will be further improved through the optimization of sidewall roughness. A summary encapsulating the key device performance indicators is then presented in Fig. 3 and Table 1. As compared to traditional silicon and lithium niobate devices, PZT exhibits a notable improvement in modulation efficiency while maintaining a high EO bandwidth[12–15] (Table 2). Furthermore, with additional structural refinements, it is anticipated that the bandwidth of PZT MZM will surpass 150 GHz[11]. Moving forward, our efforts are directed towards augmenting both the performance and versatility of the PZT optical platform by continuously refining device design and fabrication processes through iterative enhancements.

Finally, to meet the critical demands of high-performance on-chip photonic integration platforms driven by the rapid advancement of information technology, we propose three primary development directions and associated challenges for PZT materials: (1) Comprehensive high-performance PZT photonics PDK. As detailed above, achieving this goal necessitates iterative refinement of process design and fabrication techniques. Key areas include efficient and precise polarization control, electro-optic matching optimization, and advanced etching processes. These strategies aim to support high-speed, high-efficiency, and low-loss on-chip optical signal processing, addressing the requirements of high performance photonic systems. (2) Large-scale wafer-level fabrication process. Building on the current cost-effective thin-film fabrication processes, it's necessary to optimize lattice-matched growth conditions, refine thin film deposition parameters, and upgrade supporting equipment. These improvements will enable the production of large-area PZT wafers (8–12 inches), laying the groundwork for commercialization and broader photonics applications. (3) Silicon-based PZT het-

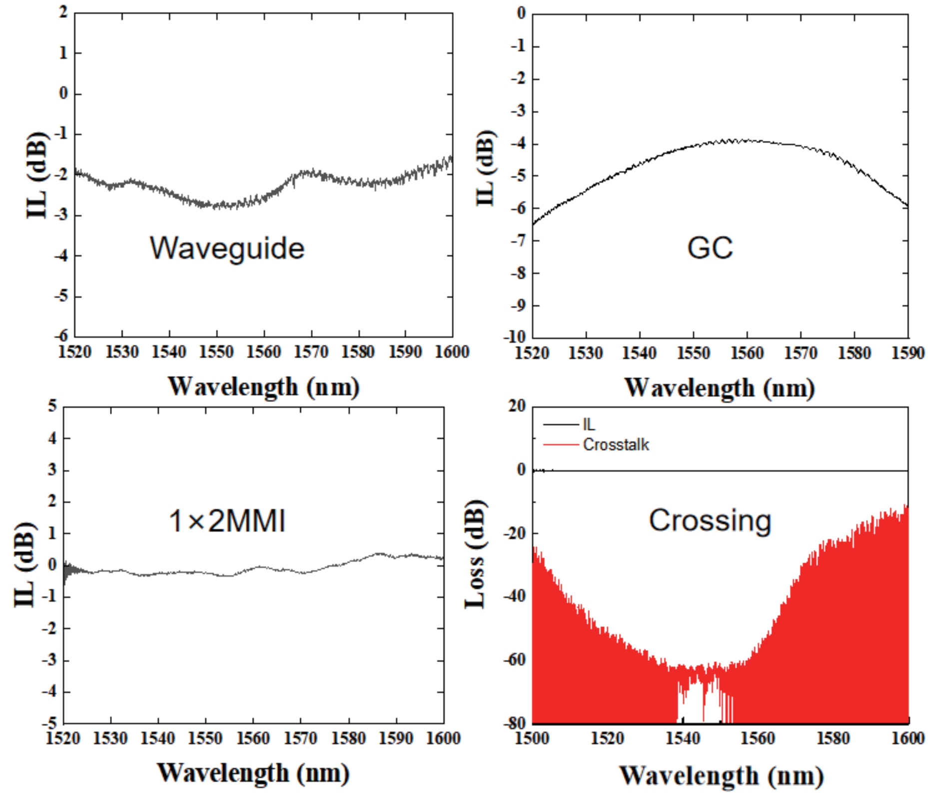

Fig. 3. (Color online) Performance results for passive PZT devices in the C-band.

Table 1. Summary of PZT devices performance.

Device	Parameter	C-band	O-band
Rib waveguide	Loss (dB/cm)	2.2	2.5
GC	Loss (dB)	4	4.6
1 × 2MMI	Loss (dB)	0.1	0.15
	Imbalance (%)	<5	<5
Crossing	Loss (dB)	0.1	0.15
	Crosstalk (dB)	<−40	<−40
MZM	Bandwidth (GHz)	>70	/
	Modulation efficiency (V·cm)	1.3	/
MRM	Bandwidth (GHz)	53	/
	Modulation efficiency (V·cm)	0.56	/

Table 2. Comparison of PZT modulator performances with TFLN and SiPhs.

Device	Materials	$V_\pi L$ (V·cm)	EO bandwidth (GHz)	Ref
MZM	SiPhs	1.9	46	[12]
MZM	TFLN	2.2	>70	[13]
MZM	TFLN	2.35	110	[14]
MZM	PZT	1.3	>70	This work
MRM	SiPhs	0.825	>50	[15]
MRM	TFLN	7	17	[16]
MRM	PZT	0.56	53	This work

erogeneous integration. It involves integrating PZT onto silicon-on-insulator (PZT-SOI) platforms during the back-end fabrication steps of SiPhs, posing challenges such as growth-temperature compatibility and the development of a robust wafer-level bonding process. By advancing monolithic heterogeneous integration techniques, we can fully harness the optical advantages of both PZT and silicon materials, thus offering a robust platform with comprehensive PZT-SOI PDK for extensive optoelectronic integration systems (Fig. 4). Overall, from our perspective, these breakthroughs especially in manufacturing technology as aforementioned will provide essential support for the practical deployment of PZT-based optical functional chips (Fig. 5).

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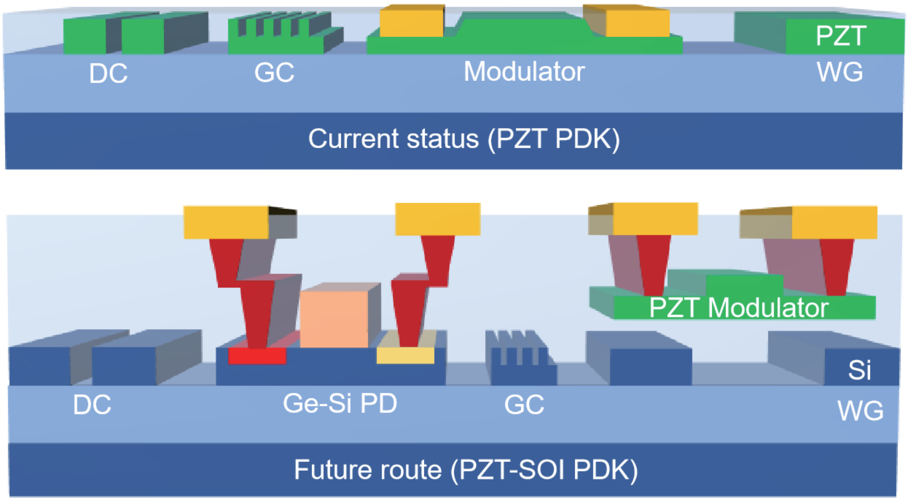

Fig. 4. (Color online) Development from PZT optical platform to PZT-SOI optical platform.

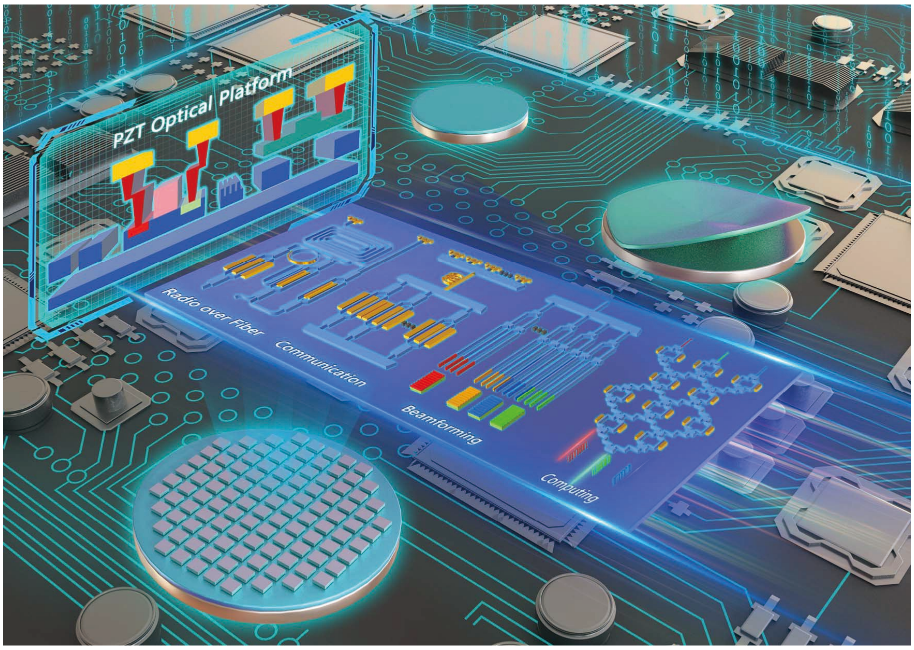

Fig. 5. (Color online) The future outlook for manufacturing technology and functional chips of PZT optical platform.

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Yujun Xie received the B.S. degree in electrical engineering and automation from Fudan University, Shanghai, China, in 2016, and the Ph.D. degree in physical electronics from Fudan University in 2021. He currently holds a position as an Assistant Researcher with the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China. His research interests include high-speed optoelectronic materials and devices.

Peng Wang received the Ph.D. degree in optoelectronics and nanostructure science from the University of Shizuoka, Hamamatsu, Japan, in 2017. He currently holds a post-doctoral position with the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China. His current research interests include high-speed optoelectronic devices and materials.

Hongyan Yu received the B.S. degree in material physics from Harbin University of Science and Technology, Harbin, Heilongjiang, China, in 2015, and received M.S. degree in optical engineering from Beijing University of Technology, Beijing, China, in 2019, and received Ph.D. degree in optical engineering from Zhejiang University, Hangzhou, Zhejiang, China, in 2023. He currently holds a post-doctoral position with the Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, Hangzhou, Zhejiang, China. His research interest includes high-speed electro-optic modulators.

Feng Qiu received the Ph.D. degree from Kochi University of Technology, Japan, in 2011. From 2011 to 2022, he was a Research Scholar and then Assistant Professor with the Institute for Materials Chemistry and Engineering, Kyushu University. In 2022, he joined the Hangzhou Institute for Advanced Study, University of Chinese Academy of Sciences, where he is now a full professor on optical and electrical materials/devices. His research aims to realize highly efficient optoelectronic devices based on novel and exciting thin film materials.

Ming Li received the Ph.D. degree in electrical and electronics engineering from the University of Shizuoka, Hamamatsu, Japan, in 2009. In 2009, he was with the Microwave Photonics Research Laboratory, School of Electrical Engineering and Computer Science, University of Ottawa, Ottawa, ON, Canada, as a Postdoctoral Research Fellow. In 2011, he was with the Ultrafast Optical Processing Group under the supervision of INRS-EMT, Montreal, QC, Canada, as a Postdoctoral Research Fellow. In 2013, he was with the Institute of Semiconductors, Chinese Academy of Sciences, Beijing, China, as a Full Professor under the support of Thousand Youth Talents Program. He has authored more than 140 high-impact journal papers. His research interests include integrated microwave photonics and its applications, ultrafast optical signal processing, and high-speed real-time optical measurement and sensing.