Planar Oxide Photonic Materials and Devices: feature issue introduction

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Abstract: Oxide materials are widely used in photonic devices. Recently, with the development of photonic integrated circuits (PICs), planar integration of oxide thin film materials and photonic devices has become an actively studied emerging field. In this feature issue, we present 12 papers in the field of planar oxide photonics. Topics include passive and active photonic devices based on oxide materials for applications in a variety of planar integrated photonic devices such as metasurfaces, optical isolators, photodetectors, modulators, light sources and nonlinear photonics.

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Oxide materials are widely used in bulk optical devices, such as prisms, lenses, polarizers, modulators, lasers and gain mediums, just to name a few. Such materials usually feature a relatively wide optical band gap in the ultraviolet, and a phonon absorption edge in the mid-infrared, therefore offering a wide transparency window from the ultraviolet to infrared wavelengths. The unique crystal and electronic band structure of oxide materials enable their wide applications in optical systems. In passive photonic devices, oxide materials with isotropic optical constants are used as lenses and prisms, such as fused-quartz, titanium dioxide (TiO2) and gadolinium gallium oxide (GGG). Oxide single crystals with anisotropy optical constants, such as calcites or quartz, are used as wave plates and polarizers. Magneto-optical oxides, a class of oxide materials with unique optical anisotropy, i.e. optical circular birefringence (or Faraday effect), are used in optical isolators and circulators to provide optical nonreciprocity to optical systems. In active photonic devices, nonlinear optical materials such as LiNbO3 and BaB2O4 are used in electro-optic modulators and other nonlinear photonic devices. Doped oxide crystals such as Nd doped yttrium aluminum garnet (Nd:YAG) and Ti doped sapphire (Ti:Al2O3) are used for solid state lasers etc.

With the development of photonic integrated circuits, an emerging field is to integrate oxide materials in a planar device structure. This field studies thin film growth, characterization, device design and fabrication of oxide material based on planar photonic devices. The research effort in this field will not only fulfill the missing functionality in PICs provided by oxide materials, but also enable novel photonic materials and devices for advanced data processing, detection, and sensing for future PICs.

In this feature issue, we present 12 papers in the field of planar oxide photonic materials including 7 invited papers and 5 contributed papers. The papers can be categorized into two topic areas, namely (i) passive oxide photonic materials and devices and (ii) active oxide photonic materials and devices. The oxide thin films studied in these papers include CMOS
compatible silicon dioxide, or functional oxide thin films heterogeneously grown on semiconductor substrates. The applications include on-chip optical phase control in metasurfaces, optical isolators and circulators, optical modulators, photodetectors and light sources. Although it is far from a complete overview of this field, we hope these papers can provide a showcase of the research advances in this active research field.

The first topic area covers two material systems, the silicon oxide/nitride materials and magneto-optical oxides, in particular rare earth doped iron garnet thin films. They focus on applications in metasurface phase control structures and planar non-reciprocal photonic devices, such as optical isolators and circulators. Four papers focus on optical isolation on-chip, which is a missing link in PIC technologies. The first paper by Y. Shoji and T. Mizumoto [1] discusses recent progress in integration of magneto-optical isolators on silicon using wafer-bonded epitaxial Ce:YIG thin films. The authors address two issues with integrated magneto-optical optical isolators by wafer bonding, i.e. the junction loss between the bonded magneto-optical thin films and the silicon waveguide, and the on-chip magnetic fields. They propose a TE mode coupler at the waveguide junctions together with a polarization rotator to significantly reduce the coupling loss. At the same time they use a FeCoB thin film remnant magnetization to provide a local magnetic field to the garnet thin films. A current switchable magneto-optical switch with latching operation was demonstrated. The paper by D. Huang et al. [2] use similar technology of bonding Ce:YIG thin films on silicon waveguides to achieve optical isolation. They address three challenges in the report, the coupling between the on-chip laser and isolator, the mismatch between the laser and isolator polarization and the on-chip magnetic field to bias the Ce:YIG thin films. They propose several process strategies and a broadband low loss polarization rotator on the silicon waveguides to solve the mode and polarization mismatch between the bonded laser and isolator. Meanwhile they use an on-chip electromagnet to provide local magnetic fields to a ring type TE mode isolator. The paper by Srinivasan et al. [3] reports a Faraday rotation type waveguide isolator device which can isolate TE- and/or TM-modes. A quasi phase matching structure is used to compensate the phase mismatch between TE and TM modes due to the waveguide birefringence. The fourth paper by J. Ding et al. [4] introduces a new magneto-optical material Tb$_3$Sc$_2$Al$_3$O$_{12}$ (TSAG) for optical isolator and circulator applications at the visible wavelengths. This material shows 20% higher Verdet constant compared to the commercial Tb$_3$Ga$_5$O$_{12}$ (TGG) crystals at the visible wavelength range. They also measured the THz transmittance of this material from 1 THz to 5 THz. A low absorption coefficient of 2 cm$^{-1}$ is observed in this material. The second material system in this topic focuses on CMOS compatible silicon oxide/nitride thin films. The paper by S. Colburn et al. [5] reviews recent progress on silicon nitride material based metasurfaces. SiN features one of the lowest index material in state-of-the-art metasurface devices. As a CMOS compatible material with wide optical transparency window, SiN is well fitted for a variety of metasurface device applications, such as visible frequency metasurface lenses, holograms, freeform surfaces, mirrors for optical cavities, computational imaging and disorder-engineered metasurfaces. The authors also discussed TiO$_2$ based metasurfaces and the possibility of developing silicon oxide/oxynitride based metasurfaces in future studies. C. Yan et al. [6] focuses on laser induced damage in fused silica materials at above laser-induced damage threshold conditions. They used 6.8 ns 355 nm laser pulse at different fluences and pulses to amblate a fused quartz sample and characterized the structural change after laser irradiation. They noticed crystallization and formation of Si-H and Si = O bonds by Raman microscopy, therefore provided information for reliability consideration in high power applications of this material.

The second topic area covers planar oxide materials and device structure for several active device applications, including optical modulators, detectors, light source and nonlinear optical applications. Two papers reported the study on transparent conductive oxide(TCO) thin films for optical modulator and nonlinear optical device applications. E. G. Carmenella et al. [7] shows the possibility to perform nonlinear optics with degenerate excitation near ENZ
(epsilon near zero) point in transparent conductive oxides. The team reports the simultaneous enhancement of both the 2nd order nonlinear Kerr coefficient and the 3rd order nonlinear susceptibility via pump probe spectroscopy in aluminum zinc oxide (AZO) films. The results show a 6 and 10-fold increase for the two nonlinear effects, respectively, at near-ENZ wavelengths. This regime is found in the telecommunication frequency band, thus enabling applications such as the design of nanophotonics devices to the study of the fundamental physics in time-varying media. The paper by Q. Gao et. al. [8] compared several models for describing the TCO material based optical modulators. The difference between classical models and the proposed quantum model indicate an underestimation of the driving voltage for optical modulation in TCO materials, therefore raised concerns on reliability issues of such devices due to dielectric breakdown. They show that the quantum model matches better with recent experimental results. They also pointed out that there may be other mechanisms that may not be understood by the quantum model. Two papers studied photodetectors based on oxide materials. The paper by Kathalingam A. et. al. [9] reported a photoconductor fabricated using solution processed Cu:ZnO nanorods and planar integrated on oxidized silicon waveguides using photolithography patterned electrodes. The Cu doped ZnO nanorods showed better photoresponse compared to ZnO materials in the ultraviolet. They demonstrate an easy fabrication process for nanorod based photoconductors. The paper by Y. Xu et. al. [10] reported a study on β-Ga2O3 based solar blind deep ultraviolet photodetectors. Using epitaxial β-Ga2O3 thin films grown on sapphire substrates and a metal-insulator-metal detector device structure, they demonstrated excellent device performance in the ultraviolet including high responsivity, low dark current, high photo to dark ratios high external quantum efficiency. X. Wang et. al. [11] provided a systematic review on Erbium doped silicate materials for waveguide integrated light source applications. The authors summarized the study on theory, material fabrication and optimization, waveguide design, waveguide light emission diodes and novel single crystal Erbium silicate nanowires, providing an overview of the cutting edge research activity in this field. Z. Lu et. al. [12] reported mode-locked soliton crystals (SCs) a high-Q (>10^6) micro-ring resonator (MRR) using high index dope silicon dioxide ring resonators. They theoretically and experimentally studied the asymmetric spectrum of SCs due to Raman self-frequency shift (RSFS) and the wavelength-dependent loss. They also estimated a Raman shock time of 2.5 fs to 2.7 fs.

The editors envision a bright future for planar oxide photonic materials and devices. We are glad to see increasingly important and diverse applications of oxide materials in PICs. Excellent performances comparable or even exceeding bulk oxide materials and devices are observed in a variety of devices in this field. Novel photonic phenomena due to the decreased modal size, strong field localization and interface effects are quickly emerging. We believe planar oxide photonic devices will become indispensable components in future PICs. We would like to appreciate all authors and reviewers for their time and effort in preparing and reviewing the manuscripts. We are also grateful to Prof. Alexandra Boltasseva, Editor-in-Chief of *Optical Materials Express* and Prof. Juejun Hu, Deputy Editor of *Optical Materials Express* for their support of this feature issue. We thank all OSA journal staff for great support during the review and publication processes.

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